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**Woods Hole
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**Seafloor Borehole Array Seismic System
(SEABASS)**

by

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G. Omnes, K. Peal, S. Swift, R. Turpening, and C. Zani**

January 1993

Technical Memorandum

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ABSTRACT

The Seafloor Borehole Array Seismic System (SEABASS) has been developed to measure the pressure and three dimensional particle velocity of the VLF sound field (2-50HZ) below the seafloor in the deep ocean (water depths of up to 6km). The system consists of four three-component borehole seismometers (with an optional hydrophone), a borehole digitizing unit, and a seafloor control and recording package. The system can be deployed using a wireline re-entry capability from a conventional research vessel in Deep Sea Drilling Project (DSDP) and Ocean Drilling Project (ODP) boreholes. Data from below the seafloor are acquired either on-board the research vessel via coaxial tether or remotely on the seafloor in a self-contained package. If necessary the data module from the seafloor package can be released independently and recovered on the surface. This paper describes the engineering specifications of SEABASS, the tests that were carried out, and preliminary results from an actual deep sea deployment. Ambient noise levels beneath the seafloor acquired on the Low Frequency Acoustic-Seismic Experiment (LFASE) are within 20dB of levels from previous seafloor borehole seismic experiments and from land borehole measurements. The ambient noise observed on LFASE decreases by up to 12dB in the upper 100m of the seafloor in a sedimentary environment.

THE SEAFLOOR BOREHOLE ARRAY SEISMIC SYSTEM (SEABASS)

Table of Contents

	<u>Page Number</u>
ABSTRACT	1
1. INTRODUCTION	4
2. THE MODIFIED MULTILOCK ARRAY	8
2.1 OVERVIEW	8
2.2 MECHANICAL SYSTEMS	9
2.3 ELECTRICAL SYSTEMS	14
2.4 SURFACE INTERFACE	17
3. THE BOTTOM INSTRUMENT PACKAGE	19
3.1 OVERVIEW	19
3.2 MECHANICAL SYSTEMS	22
3.3 CONTROL FUNCTIONS	28
3.4 CLOCKS AND TIMING	34
3.5 SEAFLOOR PROCESSING AND TELEMETRY	35
3.6 SHIPBOARD RECORDING	38
3.7 SEAFLOOR RECORDING	38
3.8 POWER CONSUMPTION	41
3.9 QUICKLOOK SHIPBOARD PROCESSING	42
3.10 POSTDEPLOYMENT PROCESSING	43
4. DESIGN CONSIDERATIONS AND SPECIFICATIONS	47
4.1 FIELD VALUES OF PRESSURE AND GROUND VELOCITY	47
4.2 INSTRUMENT AND FIELD NOISE	49
4.3 HYDROPHONE GAIN STRATEGY	60
4.4 TRANSFER FUNCTIONS	62
4.5 THE DIGITIZER AND NUMBER REPRESENTATION	68
4.6 TOOL DIMENSIONS AND USE FROM ODP DRILL SHIPS	71
4.7 TEMPERATURE SPECIFICATIONS AND HYDROTHERMAL VENTS	71
5. DEPLOYMENT CONFIGURATIONS	72
5.1 VSP CONFIGURATION	72
5.2 LAND TEST CONFIGURATION	75
5.3 AT SEA CONFIGURATION	75

6. TEST PROCEDURES WITH EXAMPLES	78
6.1 OVERVIEW	78
6.2 CALIFORNIA TEST CRUISE	78
6.3 ACCEPTANCE TESTS OF THE MODIFIED MULTILOCK TOOL	79
6.4 SHAKE TABLE TESTS	81
6.5 MAROLLES BOREHOLE TEST	86
6.6 MICHIGAN BOREHOLE TEST	86
6.7 MARTHA'S VINEYARD WET TEST	90
6.8 THE FLORIDA DEPLOYMENT (LFASE)	90
7. REDUNDANCY, SAFETY FACTORS AND RISK REDUCTION	100
7.1 OVERVIEW	100
7.2 WEAK LINKS	100
7.3 ACOUSTIC RELEASE OF TETHER AND DRU	102
7.4 ACOUSTICALLY TRIGGERED RECORDING WINDOW	103
7.5 DEFAULT RECORDING PROGRAM	103
7.6 SINGLE CABLE DESIGN	103
7.7 WATCHDOG CIRCUITRY	104
7.8 SPARE SONDE AND SPARE PARTS	104
7.9 SCAN COUNTER	104
7.10 OPTICAL DISK SEARCH PATTERNS	105
7.11 INDEPENDENT BATTERY ON CLOCK AND TRANSPONDERS	105
8. DISCUSSION AND SUMMARY	106
8.1 AMBIENT NOISE ISSUES	106
8.2 TECHNICAL ISSUES	108
9. ACKNOWLEDGEMENTS	110
10. REFERENCES	111

1. INTRODUCTION

The Seafloor Borehole Array Seismic System (SEABASS) was developed to measure the pressure and three dimensional particle velocity of the VLF sound field (2-50HZ) below the seafloor in the deep ocean (water depths up to 6km). (A summary of the acronyms used in this paper is given in Table 1-1.) The system can be deployed from a conventional research vessel in Deep Sea Drilling Project (DSDP) and Ocean Drilling Project (ODP) boreholes using the wireline re-entry capability (Spiess *et al*, 1989a; submitted). Data from below the seafloor are acquired either on-board the research vessel via coaxial tether or remotely on the seafloor in a self-contained package.

A review of borehole seismic measurements in the deep sea up to 1987 is given by Mutter and Balch(1987). Prior to the development of the SEABASS system, borehole seismic measurements in the deep sea either were obtained at only a single fixed depth, as in the Marine Seismic System (MSS; Harris *et al*, 1987; Adair *et al*, 1987) and the Ocean Subbottom Seismometer (OSS; Byrne *et al*, 1987), or were obtained directly from the drill ship and were contaminated by ship and drill pipe noise (for example, Stephen *et al*, 1980; Stephen and Harding, 1983; Stephen and Bolmer, 1985). There had been an indication from previous seismic work, both at sea and on land, that borehole seismometers had two major advantages over surface or seafloor seismometers: both ambient noise levels and signal generated noise levels (bottom reverberation or coda) decreased with depth below the solid surface and signal quality, particularly on horizontal components, was better for borehole receivers because of improved coupling to true earth motion. SEABASS was developed to provide conclusive, *in situ*, quantitative observations to test these hypotheses in a deep sea environment.

SEABASS itself consists of four borehole sondes and a data telemetry unit, based on the Multilock Seismic Tool (Compagnie Générale de Géophysique, 1987; Géomécanique and Compagnie Générale de Géophysique, 1987), and a Bottom Instrument Package (BIP), designed and built at Woods Hole Oceanographic Institution (Koelsch *et al*, 1990). Each of the borehole sondes consists of a three component seismometer (with a natural frequency of 4.5Hz) and a clamp, to couple the sonde to the borehole wall. The top sonde can have an optional borehole hydrophone attached. (With some care paid to the channel assignments and cable wiring hydrophones can be attached to any of the four sondes.) The Bottom Instrument Package is designed to internally record up to 600 Mbytes of data (41 hours of data acquisition) and to operate SEABASS autonomously on the seafloor for periods up to two months.

SEABASS is deployed in the configuration shown in Figure 1-1. The wireline re-entry technique requires a Borehole Re-entry Guide (BRG) below the borehole array, to locate the borehole on the seafloor, and a thruster above the Bottom Instrument Package, to position the array prior to re-entry. (The BRG and thruster were designed, built, and operated by the Marine Physics Laboratory of Scripps Institute of Oceanography (MPL/SIO). MPL/SIO also carried out the bottom navigation, ship dynamic positioning, borehole re-entry, and data telemetry from the BIP to the surface ship.) When SEABASS is in place the four seismic sondes are clamped at fixed positions in the borehole and the Bottom Instrument Package sits in the re-entry cone. During shipboard recording the thruster is maintained within a 100m watch

Seismic Array Deployed and in Tethered Mode

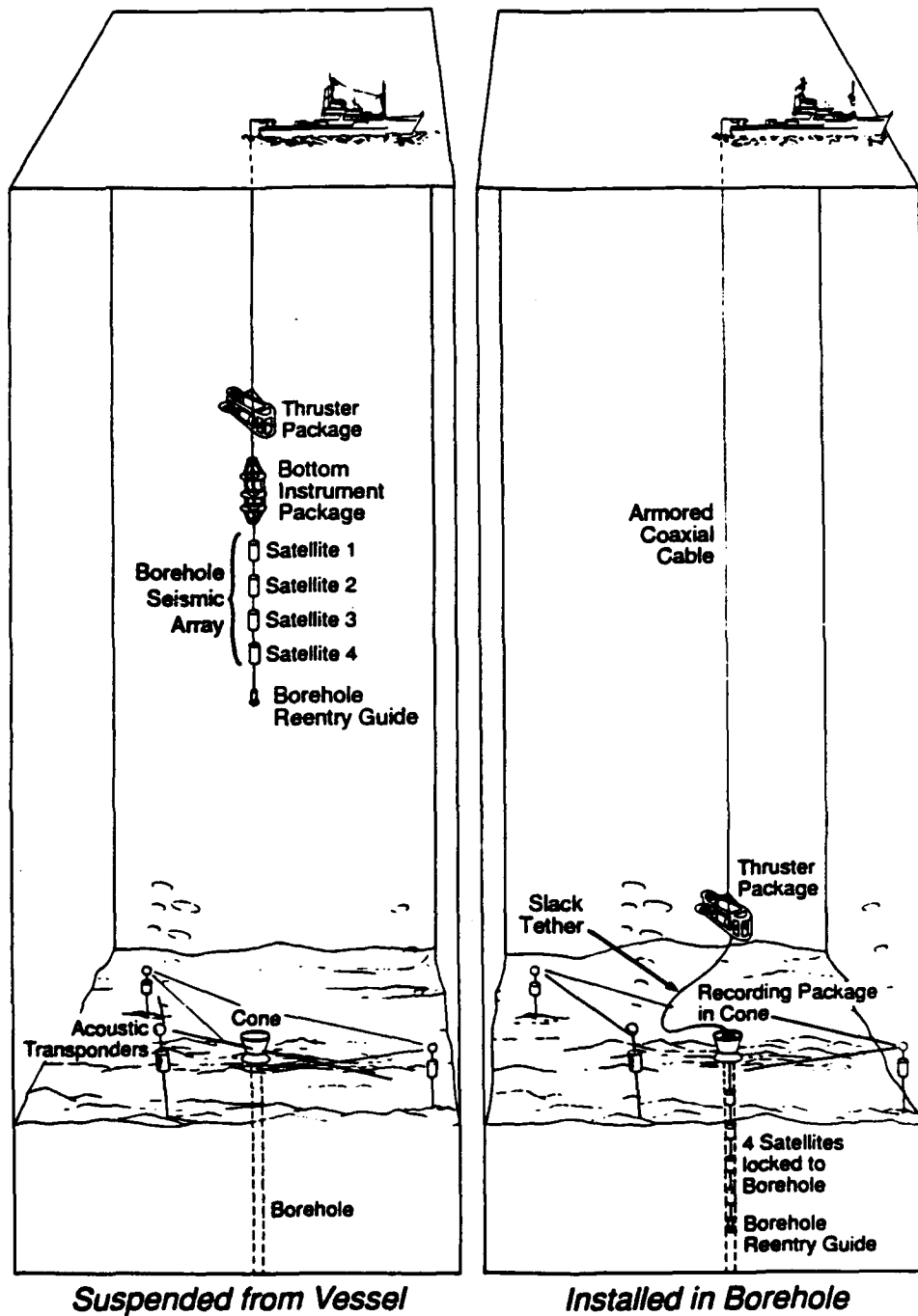


Figure 1-1. SEABASS is deployed with a re-entry system like the one used on LFASE. SEABASS consists of the Bottom Instrument Package and the four node borehole array. The Borehole Re-entry Guide is used to locate and enter the borehole and the thruster is used along with dynamic positioning on the ship to position the system above the hole. The left frame shows the system deployed in the water column. The right frame shows the system installed in the borehole in 'tethered mode'. The tether can be disconnected to leave the system operating autonomously on the seafloor.

Table 1-1 Acronyms used in this paper.

A12G4	CGG Recording Format
ADC	Analog to Digital Converter
AMG	Ateliers Mécaniques de Saint-Gaudens
APL	Applied Physics Laboratory
BCU	Bottom Control Unit
BIP	Bottom Instrument Package
BRG	Borehole Re-entry Guide
BRF	Below the Rig Floor
BSF	Below the Seafloor
BSL	Below Sea Level
CIEM	Communication and Interface Electronic Module
CGG	Compagnie Générale de Géophysique
CMOS	Complementary-Symmetry Metal Oxide Semiconductor
DAC	Digital-to-Analog Converter
DC	Direct Current
dB	decibel defined as $20 \cdot \log(\text{amplitude}/\text{reference amplitude})$
DRU	Data Recording Unit
DSDP	Deep Sea Drilling Project
DTU	Data Telemetry Unit
EEPROM	Electrically Erasable Programmable Read Only Memory
EPLD	Electrically Programmable Logic Device
EPROM	Electrically Programmable Read Only Memory
FFT	Fast Fourier Transform
GOES	Geostationary Operational Environmental Satellite
HDB3	High Density Bipolar Modulus 3
IBM	International Business Machines
ID	Inside Diameter
IFP	Institut Français du Pétrole
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer
IGPP	Institute for Geophysics and Planetary Physics
IU	Interface Unit
JHU	Johns Hopkins University
KWH	Kilowatt Hour
LFASE	Low Frequency Acoustic-Seismic Experiment
LORAN	Long Range Navigation
LOPACS	Low Power Acquisition Control Storage System
LSB	Least Significant Bit
MIT	Massachusetts Institute of Technology

Table 1-1, continued

MPL	Marine Physics Laboratory
MS-DOS	MicroSoft - Disk Operating System
MSS	Marine Seismic System
NOARL	Naval Ocean and Atmospheric Research Laboratory
NRE	Non-Recurring Engineering
NRZ	Non-Return to Zero
OAS	Ocean and Atmospheric Sciences, Inc
OBS	Ocean Bottom Seismometer
OD	Outside Diameter
ODP	Ocean Drilling Project
OSS	Ocean Sub-bottom Seismometer
PC	Personal Computer
PC/AT	Personal Computer - Advanced Technology
PC/XT	Personal Computer - Extended Technology
QLS	Quick Look System
RAM	Random Access Memory
RMS	Root Mean Square
ROM	Read Only Memory
ROSE	Rivera Ocean Seismic Experiment
R/V	Research Vessel
SAIC	Science Applications International Corporation
SATNAV	Satellite Navigation System
SCSI	Small Computer Systems Interface
SEABASS	Seafloor Borehole Array Seismic System
SIO	Scripps Institute of Oceanography
SOPEMEA	Société pour le Perfectionnement des Matériels et Equipements Aérospatiaux
ULF	Ultra-Low Frequency
USNS	United States Navy Ship
UTS	Universal Standard Time
VHA	Vertical Hydrophone Array
VLF	Very Low Frequency
VSP	Vertical Seismic Profile
WHOI	Woods Hole Oceanographic Institution
WWV	National Bureau of Standards Radio Station

circle and it is connected to the BIP by a 'slack tether'. The thruster is supported from the surface vessel by an armoured, coaxial cable. For autonomous seafloor recording, the 'slack tether' is disconnected from the BIP. Recovery is accomplished by grappling, using the thruster and a hook. If grappling fails, the Data Recording Unit (DRU) alone, a subcomponent of the BIP, can be released acoustically, allowing it to float to the surface for recovery.

The system was successfully deployed in the Blake-Bahama Basin (off the coast of Florida) in August-September, 1989 as part of the Low Frequency Acoustic Seismic Experiment (LFASE; Spiess *et al*, 1989b; submitted; Stephen *et al*, 1989; 1990). Prior to deployment of the complete system, subsystems were tested in shake-table studies (in Paris, France), two land borehole tests (near Marolles, France, and Traverse City, Michigan) and a system wet test (off Martha's Vineyard, Massachusetts).

This paper presents the specifications of SEABASS, reviews the development and testing procedures that were carried out, and gives examples of the results.

2. THE MODIFIED MULTILOCK ARRAY

2.1 OVERVIEW

The borehole array components of SEABASS are based on the Multilock Seismic Tool (Institut Français du Pétrole (1987); Compagnie Générale de Géophysique 1987; Géomécanique and Compagnie Générale de Géophysique, 1987). (The Multilock seismic system was designed by Institut Français du Pétrole. It is presently built by Ateliers Mécaniques de Saint-Gaudens (AMG) and Géomécanique and it is marketed by Compagnie Générale de Géophysique (CGG).) The Multilock system was developed as a Vertical Seismic Profile (VSP) tool for the petroleum industry. In a VSP a borehole seismometer is raised through a number of positions in the borehole while a controlled seismic source (airgun, explosion, vibrator, etc) is fired at the surface. The VSP provides interval velocities, at seismic frequencies, of the formation around the borehole and it can be used to trace the origin of subsurface reflectors. It is considered to be a valuable adjunct to surface multi-channel seismic profiles when a borehole is available. By using four sondes simultaneously the Multilock system reduces the cost of acquiring VSP profiles.

The original Multilock system consisted of four sondes, at 10m separation, which was intended for deployment in oil wells on a seven conductor logging cable. Each sonde contained a three component seismometer and was individually clamped. The top sonde, based on the Geolock H Tool (Ateliers Mécaniques de Saint-Gaudens, 1984), contained the Data Telemetry Unit with amplifiers, digitizers and telemetry electronics for twelve channels. Since the top sonde was longer and heavier than the lower sondes (or satellites) it had a hydraulic clamping mechanism. The satellites had a coil spring clamping mechanism. A surface unit was supplied for controlling the clamping arms, carrying out in-situ quality control checks on the array, and relaying the data to tape and paper recorders. In the 12 channel configuration, the

commercially available system had a passband of 10-150Hz, a sampling interval of 2msec and it used geophones with a natural frequency of 10Hz. There was an option in the original Multilock to process only six channels, say from two three-component sondes, with a passband of 10-300Hz at a sampling interval of 1msec.

Preliminary field tests of the array had shown that excellent quality data were obtained on the three satellite sondes. Resonances, particularly on horizontal components, which had appeared on other borehole seismometers were not present for the satellite sondes. The Multilock system was chosen for SEABASS because it was the only borehole seismic array that was commercially available at the time (1987) and because the response of the clamped satellites was as good as, or better than, other borehole seismometers in the petroleum industry at the time.

The major modifications to the Multilock tool that were necessary for SEABASS were: i) The DTU was made into a separate (unclamped) sonde that could either be run down the borehole for conventional VSP's or be placed in the Bottom Instrument Package for a fixed seafloor operation. ii) Below the DTU would be four essentially identical satellites with a separation of either 10m or 30m. iii) The frequency response of the system would be changed to 2.5-40Hz using geophones with a natural frequency of 4.5Hz. iv) An optional borehole hydrophone could be attached to the top node. v) Telemetry and power supply functions in the DTU were modified for operation over a short cable to other electronics packages and batteries on the BIP frame. vi) The original Multilock was specified for operation to 180°C for use in deep, hot boreholes on land or from drilling platforms in shallow water. Since the modified unit was intended primarily for seafloor use the temperature specification was reduced to 0-20°C with the primary operating temperature at 0°C. vii) In order to deploy the array in boreholes on the seafloor using the wireline re-entry technique it was necessary to pass four additional conductors through the whole array to the BRG.

The modified Multilock can be used in three configurations. It can be run as a normal four sonde VSP tool on seven conductor logging cable. (In fact, by replacing the geophone cartridge and filter boards, the modified system can have the same passband and functionality as the original Multilock.) Secondly, the system can be run as a fixed borehole array in a land or offshore borehole with the DTU and acquisition electronics in a recording hut. Thirdly, the system can be deployed as a fixed array in the deep sea floor with self contained recording capability as in SEABASS.

2.2 MECHANICAL SYSTEMS

Mechanically the borehole array component of SEABASS consists of four satellites and a Data Telemetry Unit (DTU) housing (Ateliers Mécaniques de Saint-Gaudens, 1988a; 1988b) (There is one spare complete satellite including a hydrophone for the existing system.) The borehole system is designed to operate for up to three months in seawater up to a depth of 7,000m and a temperature of 0°C.

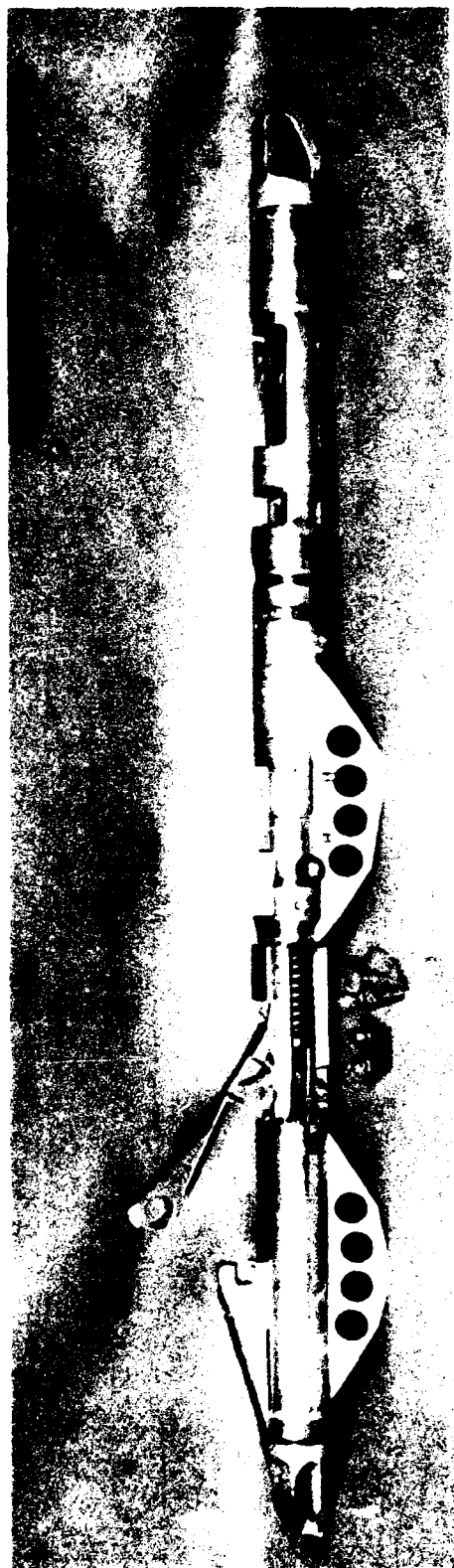


Figure 2.2-1. Each node of the Multilock array on SEABASS consists of a three component seismometer with a clamping arm and pads. The optional borehole hydrophone is attached.

The satellites (Figure 2.2-1) are mechanically interchangeable. The top and bottom connectors on each satellite are 34 pin tool heads. Each satellite contains a pair of vertical component geophones, two orthogonal pairs of horizontal component geophones and a clamping arm for coupling the geophone to the borehole wall. A hydrophone unit can be added to the top satellite as an option. Each standard satellite is 1.05m (41.2inch) long. The satellite with a hydrophone attached is 1.58m (62.1inch) long. The basic units have an outside diameter of 112mm (4.39inch). A standard satellite without hydrophone or arms and pads weighs 32.0kg(70.5lbs) in air. The satellite with a hydrophone attached weighs 46.9kg(103.5lbs) without arms and pads.

A selection of arms and removable back pads are available to provide for secure coupling in boreholes ranging from 178mm(7.0inch) to 407mm(16.0in)(Table 2.2-1). Figure 2.2-2 summarizes the geometry of a satellite configured for boreholes up to 330mm(13.0inch) and 407mm(16.0inch) in diameter. The clamping arm and two pads are located 120° from each other. The anchoring force for both configurations is 53daN(117lb) with 86% of the force being applied at the pads directly in line with the geophone package.

The DTU is a separate borehole unit which does not have a clamping mechanism. The lower end of the DTU is a 34 pin tool head. The upper end of the DTU can either be a 7 conductor well logging head, for VSP operation, or a 14 pin bulkhead connector for connection to the Bottom Control Unit (BCU) electronics in the seafloor mode. The outside diameter of the DTU housing is 103mm(4.05inch) and the length is 1480mm(58.34inch).

The cable connecting the four sondes and the DTU is 36 conductor (eighteen twisted pairs) double armoured logging cable with an outside diameter of 16mm(0.65in) (Câbles Vector S.A., 1988). The breaking strength is 12 metric tons (26,400 pounds) and cable resistance is 138Ω/km(42Ω/1,000ft). However the cable heads, connecting the cable to the tools, have only 34 pins as required by the electronics (Berteaux and Gould, 1989). This leaves one twisted pair in the cables for redundancy. The existing SEABASS system has four 30m cables, four 10m cables and one 70m cable terminated at both ends. For VSP's a fixed separation of 10m is used between sondes. The initial seafloor deployment (LFASE) used a fixed separation of 30m. The 70m cable is required for land testing. However the selection of 10m, 30m, and 70m cables permits variable spacing for the seafloor deployments if necessary or desired. One 10m cable, terminated at one end only, is available to connect to the Borehole Re-entry Guide (BRG) for seafloor operation. A blank bull-nosed end plug terminates the bottom of the fourth satellite when the array is used in VSP mode.

Shear pins are built into the lower connector of each cable to provide weak links in case a sonde is stuck in the hole. These are designed so that the shear pins will separate before any of the components higher in the string mechanically fail. In the event of a shear pin separation, a clean, well-defined connection is left in the hole that can be 'fished' using a variety of tools on either a wireline or drill string.

TABLE: 2.2-1: Satellite Configurations

<u>Maximum Borehole Diameter</u>	<u>OD of Tool with Pads and Arms Before Being Released</u>	<u>Applied Force at Maximum Diameter</u>
178mm	5.44inch	65daN 143lb
229mm	5.44inch	64daN 141lb
330mm	9.36inch	53daN 117lb
407mm	10.47inch	53daN 117lb

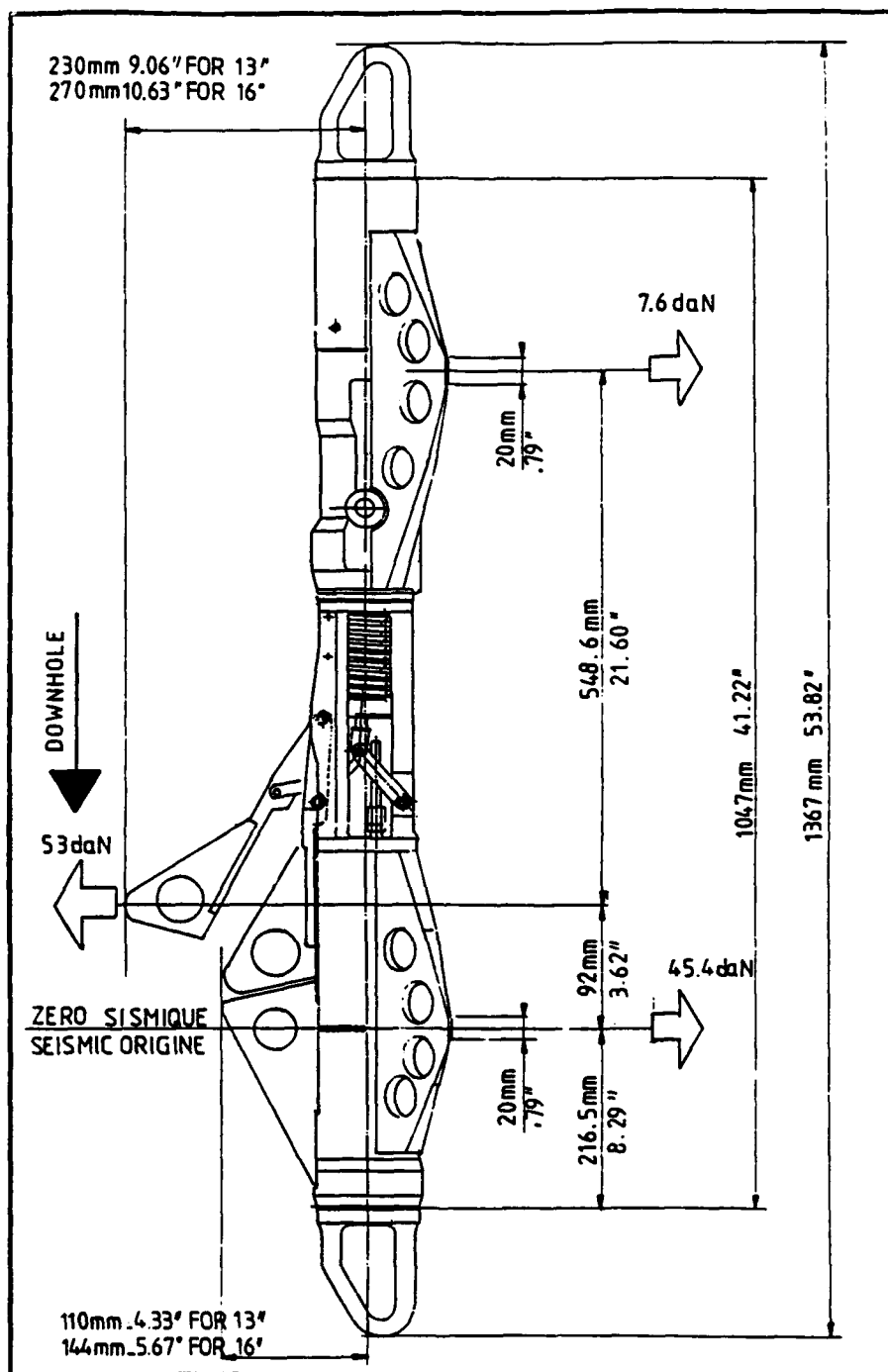


Figure 2.2-2. A suite of pads and arms are available to clamp the sondes in boreholes ranging from 178mm(7.0inch) to 407mm(16inch). This figure shows the points of contact with the well and the forces applied at each point for the 330mm(13inch) and 406mm(16inch) configurations. There are two pads (front and back in this figure) located at 120° from the clamping arm. This improves the response on the horizontal components. (This figure is from Ateliers Mécaniques de Saint-Gaudens, 1988c.)

2.3 ELECTRICAL SYSTEMS

The ground motion transducer in SEABASS is a Mark Products L-15-LBTWHT long-travel geophone with a natural frequency of 4.5Hz, a coil resistance of 600 Ω and a moving mass of 23gm. Each geophone is damped to 60% of critical with a 2.87K Ω resistor. (In the field tests in Marolles, France, and Michigan the geophones were damped to 50% of critical.) The geophone transfer function is given in Section 4.4 (Mark Products, 1989). Each of the three orthogonal components (one vertical axis and two horizontal axes) consists of two geophones in series. The 'long travel' version of the L-15 geophone operates to specifications with tilts up to 25° for the vertical sensors and up to 5° for the horizontal sensors.

The pressure transducer in SEABASS is a hydrophone built by Ocean and Atmospheric Science, Inc (Model E-2SD). It has a sensitivity of -187dB re:1 Volt/Pascal. Since the hydrophone is a capacitive device a hydrophone preamplifier is necessary before sending signals up the cable to the DTU. The hydrophone and its preamplifier are attached to the top of the first node and the hydrophone signal is substituted for one of the horizontal components in the third node. The output impedance of the hydrophone preamplifier is 1,000 Ω (compared to 992 Ω for the pair of geophones).

The hydrophone housing, which connects to the top of the top satellite and to the 34 pin cable connector, is manufactured by CCG/AMG. The hydrophone preamplifier is provided by WHOI. Because of program constraints during the design stage of SEABASS, the hydrophone preamplifier design was based on a pre-existing design from WHOI. (We had the option of using either a -12dB or 34dB built-in preamplifier with the transducer. We also had the option of reducing the gain in the Digital Telemetry Unit from 66dB to 20dB for the hydrophone channel. A discussion of the hydrophone gain strategy is given in Section 4.3.) To reduce confusion in this paper, 'preamplifier' refers only to the hydrophone preamplifier located in the hydrophone housing on the top satellite. There are also twelve 'DTU amplifiers', one for each channel, which are located with the filters in the DTU. In other manuals these are also referred to as preamplifiers.

The original Multilock had a pressure gauge to measure the hydraulic pressure in the clamping arm of the DTU and the same gauge could be used to obtain a depth measurement in the well. This was disconnected for the SEABASS system since the DTU housing in SEABASS is unclamped.

Each of the twelve transducer signals is transmitted analog on a twisted pair of wires to the Data Telemetry Unit (DTU; Géomécanique and Compagnie Générale de Géophysique, 1988b). The DTU contains amplifiers, filters, a twelve channel digitizer, state-of-health electronics and telemetry electronics. (The modifications that were made to the DTU for SEABASS are described in Géomécanique, 1988b; 1988d). They included reducing the frequency response by about a factor of four (from 10-150Hz to 2.5-40Hz), reducing the power

consumption, and providing an optional 20dB gain amplifier for the hydrophone channel in place of the usual 66dB amplifier.)

The high cut filter in the modified DTU has a 3dB point at about 40Hz with a roll off of 60dB per octave. The low cut filter in the amplifier section has a 3dB point between 2.0 and 2.5Hz with a roll off of 6dB per octave. This is combined with a similar low cut filter built into the digitizer electronics for a total low pass response of 6dB down between 2.0 and 2.5 Hz and a roll off of 12dB/octave. (The SEABASS transfer function is given in Section 4.4.)

The digitizer in the modified system samples the twelve channels at 2msec intervals as in the original Multilock, even though the frequency response of the modified system is a factor of four lower. Subsampling for recording purposes is carried out either in the surface Interface Unit during VSP's, or in the Bottom Control Unit (BCU) during seafloor acquisition.

The command frequency of the 'signal test' function is a factor of four less than the original Multilock so that all test sequence times occur at a slower rate. This 'signal test' or 'pulse test' is described in Géomécannique and Compagnie Générale de Géophysique (1988a). It is applied in the DTU *in situ* and consists of a 'geophone test' (a pulse is applied on the geophone output), a 'filter test' (the geophone is disconnected and a pulse is applied on the output of a test resistor), and an 'electronic noise test' (data are acquired with the geophone replaced by the test resistor). A fourth useful test is the 'field noise test' where data are acquired with the geophone in place. The test resistance in the modified DTU is 470 Ω , to be compatible with the original Multilock, even though the equivalent resistance of the geophone assembly is 992 Ω .

Power consumption in the modified DTU is less than in the original DTU because of changes in the operational amplifiers in the amplifier/filter stage, modifications to the data transmission amplifier and modifications to the power supply. The new operational amplifiers are only rated to 125°C rather than the 180°C in the original design. We are accepting a reduced temperature specification in order to meet the low power and low electronic noise requirements of the seafloor system.

The data transmission amplifier can be switched for low power, short distance transmission (between the DTU and BCU on the seafloor) or high power transmission over a logging cable (for VSP's). The data telemetry format in both seafloor recording and VSP modes is 'HDB3' (Boulvin, 1974). In seafloor mode 'HDB3' is converted to 'Non Return to Zero (NRZ) plus clock' (Athey, 1966) in the BCU.

The power supply unit in the DTU can also be switched between battery operation (as used for seafloor recording) and logging cable operation (as used in VSP operations with a surface power supply). In local battery operation the power consumption of the DTU is 9.1Watts (380 mamps at 24V).

Conductor assignments in the 34 pin cable heads of the borehole array are summarized in Table 2.3-1. Two conductors are used to activate the release of the clamping

Table 2.3-1. Pin assignments in the 34 conductor cable heads.

Pin	Signal Name	Description
1	Ewa4	Clamping arm sense switch
2	Wa4n	Clamping arm sense switch neutral
3	EV	Electro-valve clamping arm release voltage
4	MM	Ground
5	VS1	Vertical, Satellite #1
6	VS1n	Vertical, Satellite #1, neutral
7	VS2	Transverse Horizontal, Satellite #1
8	VS2n	Transverse Horizontal, Satellite #1, neutral
9	VS3	Radial Horizontal, Satellite #1
10	VS3n	Radial Horizontal, Satellite #1, neutral
11	VS4	Vertical, Satellite #2
12	VS4n	Vertical, Satellite #2, neutral
13	VS5	Transverse Horizontal, Satellite #2
14	VS5n	Transverse Horizontal, Satellite #2, neutral
15	VS6	Radial Horizontal, Satellite #2
16	VS6n	Radial Horizontal, Satellite #2, neutral
17	VS7	Vertical, Satellite #3
18	VS7n	Vertical, Satellite #3, neutral
19	VS8	Transverse Horizontal, Satellite #3
20	VS8n	Transverse Horizontal, Satellite #3, neutral
21	VS9	Hydrophone, Satellite #1
22	VS9n	Hydrophone, Satellite #1, neutral
23	VS10	Vertical, Satellite #4
24	VS10n	Vertical, Satellite #4, neutral
25	VS11	Transverse Horizontal, Satellite #4
26	VS11n	Transverse Horizontal, Satellite #4, neutral
27	VS12	Radial Horizontal, Satellite #4
28	VS12n	Radial Horizontal, Satellite #4, neutral
29	+13V	Hydrophone Power
30	MM	Ground
31	BRG1	Power or signal to BRG
32	BRG2	" " " " "
33	BRG3	" " " " "
34	BRG4	" " " " "

arms and two conductors are used to sense whether the clamping arms have released. Twelve twisted pairs are used to carry the analog geophone signals from the sondes to the DTU. Two lines are used to power the hydrophone preamplifier in the top sonde. Four conductors completely pass through SEABASS (from the telemetry unit in the BCU to the bottom sonde) in order to power and operate the Borehole Re-entry Guide.

During VSP operation the DTU goes down the well on a seven conductor cable (for example, Câbles Vector S.A., 1986a; 1986b). The wire assignments are given in Table 2.3-2. One line each is used to send power to the DTU and to release the clamping arms. A command line is used to choose between arm release, pulse test, and data acquisition modes. An ACQUISYNCHRO line controls the initiation and termination of a data acquisition window. One line monitors borehole pressure but this was not used in SEABASS. A sixth line sends 'Sync out' information and the seventh transmits the digital data stream. Armour provides a common system ground.

In seafloor operations a 14 conductor cable connects the DTU to the BCU (Table 2.3-3). In addition to the seven conductor assignments for logging cable operation we have separate grounds for the command line and for the digital data line and we pass four conductors directly to the BRG leads. One conductor is spare.

2.4 SURFACE INTERFACE

The surface equipment for the Multilock system in VSP mode consists of a Control Box for the clamping arms and an Interface Unit (IU) to operate and process data from the downhole Data Telemetry Unit (DTU). The Control Box simply transmits the necessary pulse to release the clamping arms. Once released the arms stay open and the tools are dragged up the hole. The Interface Unit has a number of functions (Géomécanique and Compagnie Générale de Géophysique, 1988a, 1988c). i) It triggers a test sequence in the DTU to carry out state-of health checks and processes the results for quicklook display. ii) It demultiplexes the data stream and converts the twelve digital channels to analog outputs for display on an oscilloscope or ultraviolet paper recorder. iii) It provides an interface between the borehole equipment and a digital recorder on the surface. iv) It displays the values in the auxilliary function channels (DTU temperature, power supply voltage, test pulse reference voltage, DC offset in the digitizer, and number of arms open). v) In VSP mode the IU also provides the power for the DTU electronics. vi) The modified Multilock Interface Unit can subsample a 2msec data stream to generate an 8msec data stream or it can accept an 8msec data stream directly. vii) The IU, as modified for SEABASS, accepts data in either HDB3 or NRZ-plus-clock telemetry formats. viii) Raw values of time series and spectra can be dumped to the screen for quality control checks. The modifications that were made to the IU for SEABASS are described in Géomécanique(1988b; 1988c).

Software in the Interface Unit processes the digital data stream for real time testing of the system. The IU has a DTU test mode and a maintenance test mode. The DTU test mode provides a useful quicklook capability of the data on all twelve channels. i) It displays RMS

Table 2.3-2. Pin assignments in the 7 conductor logging cable
(VSP mode)

Pin	Description
1	DTU Power Supply Input
2	Electro-valve power supply input (to release clamping arms)
3	AQUISYNCHRO Pulse
4	Command Line (+24V for electro-valves, -24V for pulse test, 0V for geophone)
5	Pressure (not used in SEABASS)
6	Sync Out
7	Digital data stream
Armour	System ground

Table 2.3-3. Pin assignments in the 14 conductor DTU-BCU connection (Seafloor Operations)

Pin	Description
1	Power supply
2	Electro-valve power supply input (110VDC)
3	Electro-valve common
4	Sync down
5	Sync up
6	Command Line (+24V for electro-valves, -24V for pulse test, 0V for geophone)
7	Command common
8	Data +
9	Data -
10	BRG 1
11	BRG 2
12	BRG 3
13	BRG 4

levels and DC offset for field noise (signals from the geophones) and for electronic noise (geophones replaced with equivalent test resistors). ii) RMS levels are displayed for the geophone test (pulse applied to geophones). iii) The A/D converter is checked by compiling statistics on the presence of bits in the mantissa and gain numbers. iv) For the filter test (pulse applied to electronics) the IU computes an FFT and displays the amplitude at 16Hz and the amplitude ratios between 16 and 2.4Hz and between 16 and 40Hz (for data sampled at 8msec).

The IU can also carry out maintenance tests of data one channel at a time. i) The user can specify a channel number, start time and duration and the IU displays DC offset and RMS value. ii) If the input time series is a pulse test, then depending on the specified start time and duration, the IU will display DC offset and RMS value for the electronic noise, geophone test and filter test. iii) To check the acquisition software and hardware the IU can compute the RMS value for a reference sine wave. iv) Harmonic distortion can be checked at fundamental frequencies of 3.906, 7.812 and 15.625Hz. v) Spectra are computed and displayed for any of the pulse test functions, the reference sine wave or raw data. A summary of noise per octave between 0.9 and 62.5 Hz is also displayed. vi) Crosstalk can be checked in the lab by applying a reference signal on one channel in the cable and the IU displays the distortion on all twelve channels and the number of harmonics used for the computation.

3. THE BOTTOM INSTRUMENT PACKAGE

3.1 OVERVIEW

The Bottom Instrument Package (BIP) sits in the re-entry cone during seafloor operations and controls the borehole array functions (Figures 3.1-1 and 3.1-2). The BIP can be either tethered to the surface ship (via the soft tether, thruster and 0.68in coaxial cable) or it can function autonomously on the seafloor.

In both tethered and autonomous seafloor operation the BIP has the following functions. i) In order to conserve power in the seafloor batteries, all electronics in the seafloor system are switched off between data acquisition intervals except for a low power 'Wake Up' circuit. ii) The BIP automatically subsamples the 2msec data stream from the DTU to an 8msec data stream and maintains the functionality of the auxilliary channels. iii) An internal clock on the BIP provides accurate first sample times for each data record. iv) A scan count is tagged to each scan to check for integrity in the data telemetry and recording stages. (Scans and scan counts are discussed further in Section 3.5.) v) State-of-health functions are monitored.

During tethered operation the BIP has the following functions: i) On surface command the BIP passes the signal to release the clamping arms in the four borehole sondes. ii) The BIP telemeters the digitized seismic data stream to the surface. iii) On either electrical command (via the tether) or acoustic command (via acoustic transponders on the BIP) the tether can be released to initiate 'sea floor recording' mode. iv) The BCU clock on the seafloor can be strobed to compare its time with the shipboard GOES clock. Any clock drifts can be detected *in situ* and corrections can be applied in postprocessing.

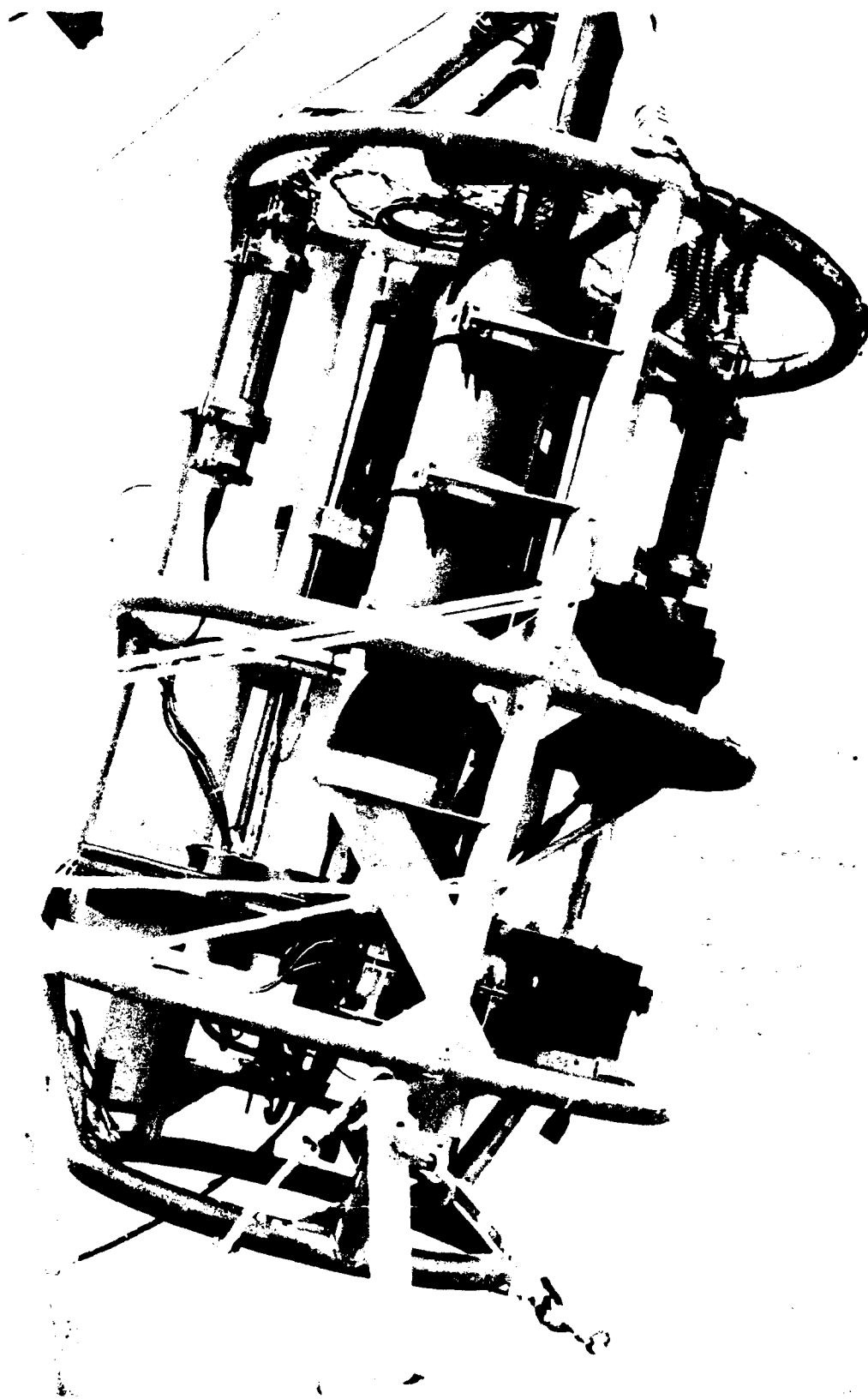


Figure 3.1-1. The Bottom Instrument Package (BIP) is designed to sit in the re-entry cone on the seafloor. It contains command and control electronics, batteries and data recorders.

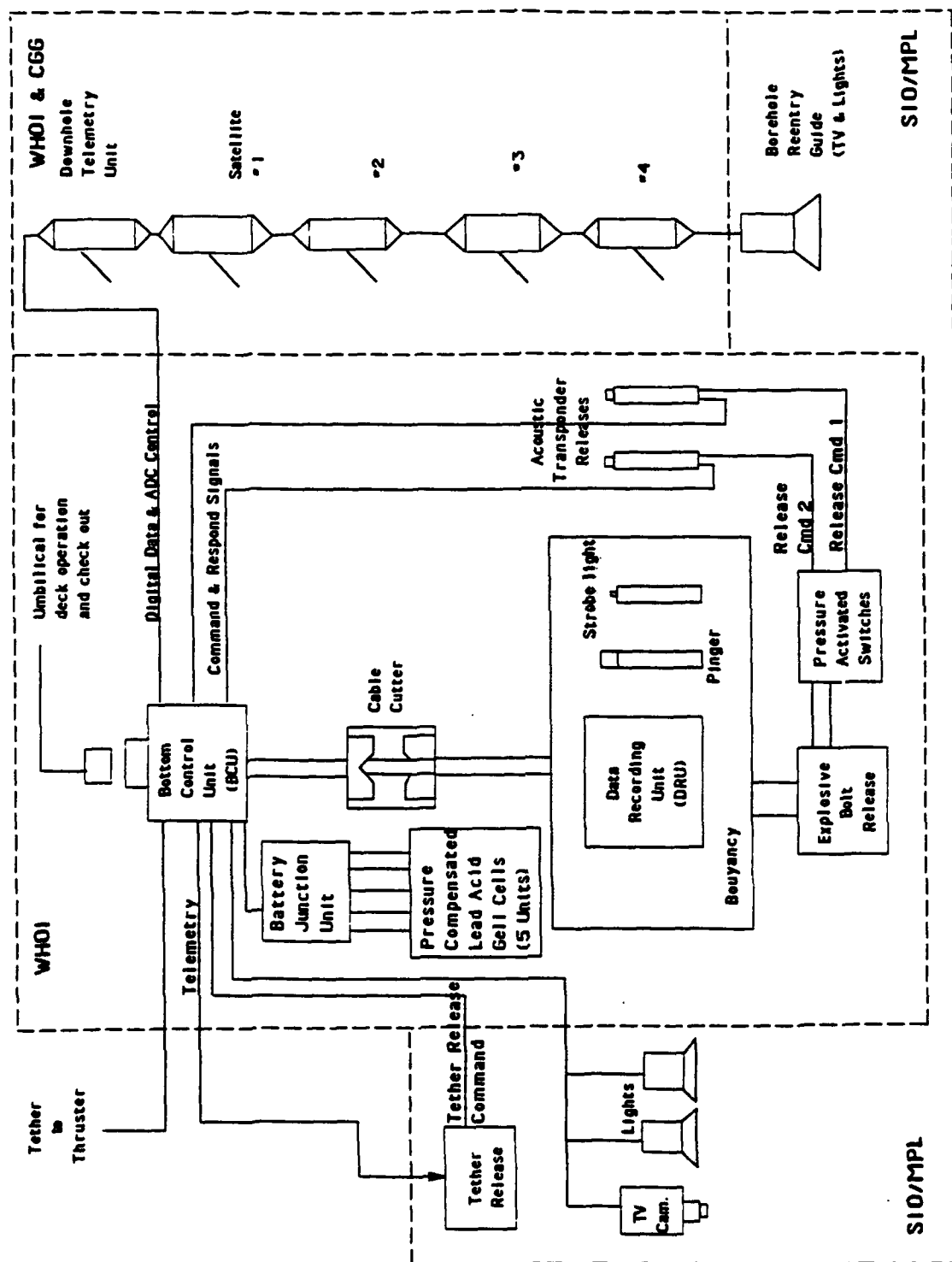


Figure 3.1-2. The various components of the Bottom Instrument Package (BIP) and borehole array, which are shown here, are described in the text. The communication and interface electronic module (CIEM) is located in the BCU. A sixth battery, which is not shown, is used to provide additional power for the MPL/SIO systems.

During autonomous seafloor operation the BIP has the following functions: i) The data stream is recorded on optical disks in the Data Recording Unit (DRU). Records are acquired on a preprogrammed schedule or on acoustic command. ii) On acoustic command the DRU can be released to float to the surface. iii) 'Watchdog' circuitry checks to ensure that the microprocessor in the Bottom Control Unit (BCU) is functioning and, if not, reboots the microprocessor.

3.2 MECHANICAL SYSTEMS

The Bottom Instrument Package (BIP) frame contains all of the pressure housings for the seafloor equipment including the DRU(with release system), BCU, DTU, cable cutter, cable release, two acoustic releases, six batteries (five batteries for the BCU and one battery for the BRG), and the television for the re-entry operation (Bocconcelli *et al*, 1991). The BIP fits in the re-entry cone on the seafloor (Figure 3.2-1; Deep Sea Drilling Project, 1983) and protrudes at least 1m above the edge of the cone so that it can be recovered by grappling. The frame, which is 3.56m(11.7feet) high with a maximum diameter of 1.83m(6.0feet), is also small enough for easy handling on deck and it is short enough to clear the A-frame on the R/V Melville. All instruments and wiring are located inside the frame to protect against damage from the re-entry cone, from the recovery hook and during shipboard handling.

To satisfy weight, strength and corrosion requirements the structure is built of welded aluminum (6061-T6) and weighs 272kg(600lbs) in air and 222kg(490lbs) in water. The main structure consists of 76mm(3.0inch) OD (schedule 40) pipes (Figure 3.2-2). Holes are drilled throughout the frame to allow quick flooding of the pipes during deployment. Sacrificial zinc anodes are placed at several locations on the frame and all instruments are insulated from their mounts with neoprene pads and delrin bushings. Fiberglass grating is used as a mounting base for the batteries and junction box. The frame has a low center of gravity to maximize stability. The frame shearing strength has been tested to 4,546daN(10,000lbs) which is greater than the strength of the top satellite shearing pin (Table 7.2-1).

The Data Telemetry Unit (DTU) is located in the middle/lower section of the frame. (The DTU is a component of the Multilock array built by CGG. See Section 2.3.) The main components are: amplifiers, filters, variable gain amplifiers, an analog-to-digital converter, a telemetry unit and a power supply. The housing material is stainless steel (AISI 431). The length of the housing is 1480mm(58.25inch) and the maximum outside diameter is 102mm(4.0inches). The unit weighs 54.4kg(120lbs) in air and 9.0kg(20lbs) in water. The DTU is mounted through the middle and lower hub of the frame and it is held in position with split bushings made of PVC. The DTU is connected to the first satellite by a section of 34 conductor electromechanical cable using the CGG cable head. It is connected to the BCU electronics housing via a 14 conductor bulkhead connector at the top end.

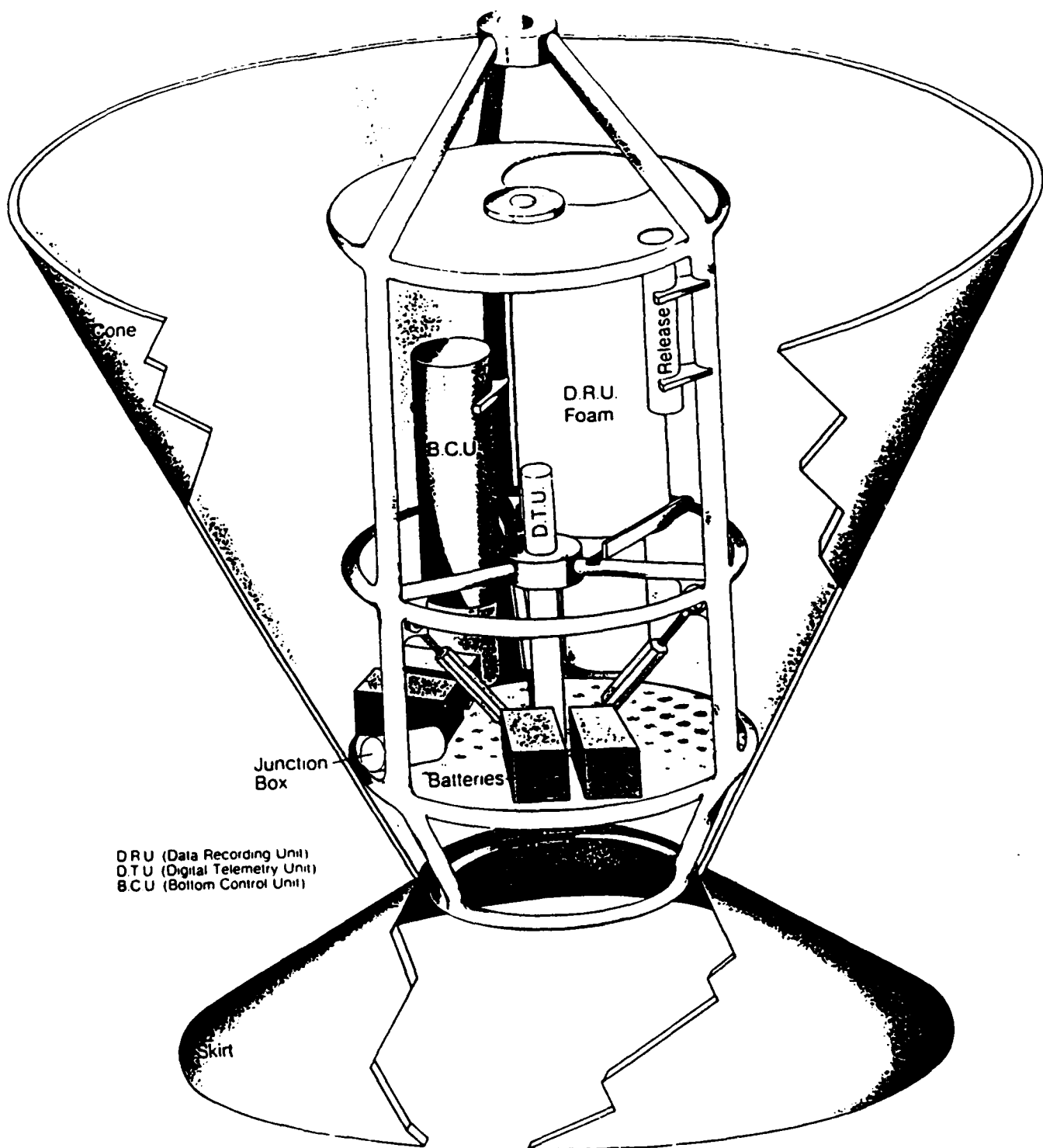


Figure 3.2-2. This schematic diagram of the BIP in the re-entry cone shows the location of the principal mechanical components on the frame.

The Bottom Control Unit (BCU) housing is a 305mm(12in)OD, 254mm(10in)ID cylindrical pressure case 1270mm(50inch) long. It provides space for the BCU clock, the BCU microprocessor, power supplies, interface electronics to the DTU and the communication and interface electronic module (CIEM, provided by MPL/SIO) which handles the telemetry from the BCU to the ship. A space 203mm(8.0inch) long in the BCU housing is reserved for the CIEM. The BCU housing is made of anodized aluminum (7075-T6). The weight is 163.3kg(360lbs) in air and 59.9kg(132lbs) in water. Seven bulkhead connectors are located in the end caps for communication to the batteries, the ship (via the thruster), the DRU, the DTU, two acoustic transponders, and the electromechanical tether release, television and lights (Figure 3.2-3).

The Data Recording Unit (DRU) pressure housing has the same dimensions as the BCU pressure housing. It contains three optical disk drives, for recording data autonomously on the seafloor, and power supplies. Since the DRU contains the experimental data, its recovery is imperative. If the bottom frame is stuck in the re-entry cone or the thruster is unable to grapple the frame, then the DRU can be released on acoustic command to float to the surface. For this purpose it is fabricated as a buoyant module.

The DRU includes an external molded floatation module which provides enough buoyancy to float the DRU to the surface when released (Figure 3.2-4). The floatation consists of six syntactic foam rings with a density of 690kg/m^3 (43.4lbs/ft^3). The total weight in air is 340kg(751lbs) and in water the package has a buoyancy of 60kg(130lbs). One bulkhead connector provides communication to the BCU via a thirty conductor cable. A pressure operated strobe light and a VHF radio beacon are located at the tip of the module to aid surface location and recovery. An acoustic pinger is also mounted on the bottom of the module to track its ascent path after release from the frame.

The DRU module sits on a spring loaded, sliding carriage which can launch the module on acoustic command. The spring power is provided by 'bungee' cords via a system of pulleys. When installed the 'bungee' cords are permanently under tension and the DRU is held to the BIP frame by two explosive bolts. The two explosive bolts are connected to separate transponders and can be fired on acoustic command. If either explosive bolt fires, the DRU is free to escape. Propelled by its buoyancy and the 'bungee' cords, the DRU pulls on a guillotine-style cable cutter, which severs the thirty conductor cable to the BCU. The syntactic foam provides sufficient buoyancy to bring the module back to the surface. Several dock tests showed that the DRU could be launched successfully from the BIP frame at angles up to 45° .

The acoustic transponders provide communication with the BIP when the tether is disconnected or inactive. Acoustic commands can be used to disconnect the tether, release the DRU or initiate a data acquisition interval. Both transponders have the same functionality and two are used to provide redundancy. Each acoustic transponder (EG&G Ocean Products, 1985; Model BACS 8202, Deep Acoustic Transponder Release) weighs 45.4kg(100lbs) in air and 31.7kg(70lbs) in water. The depth rating is 6,000m. The mooring release mechanism on the

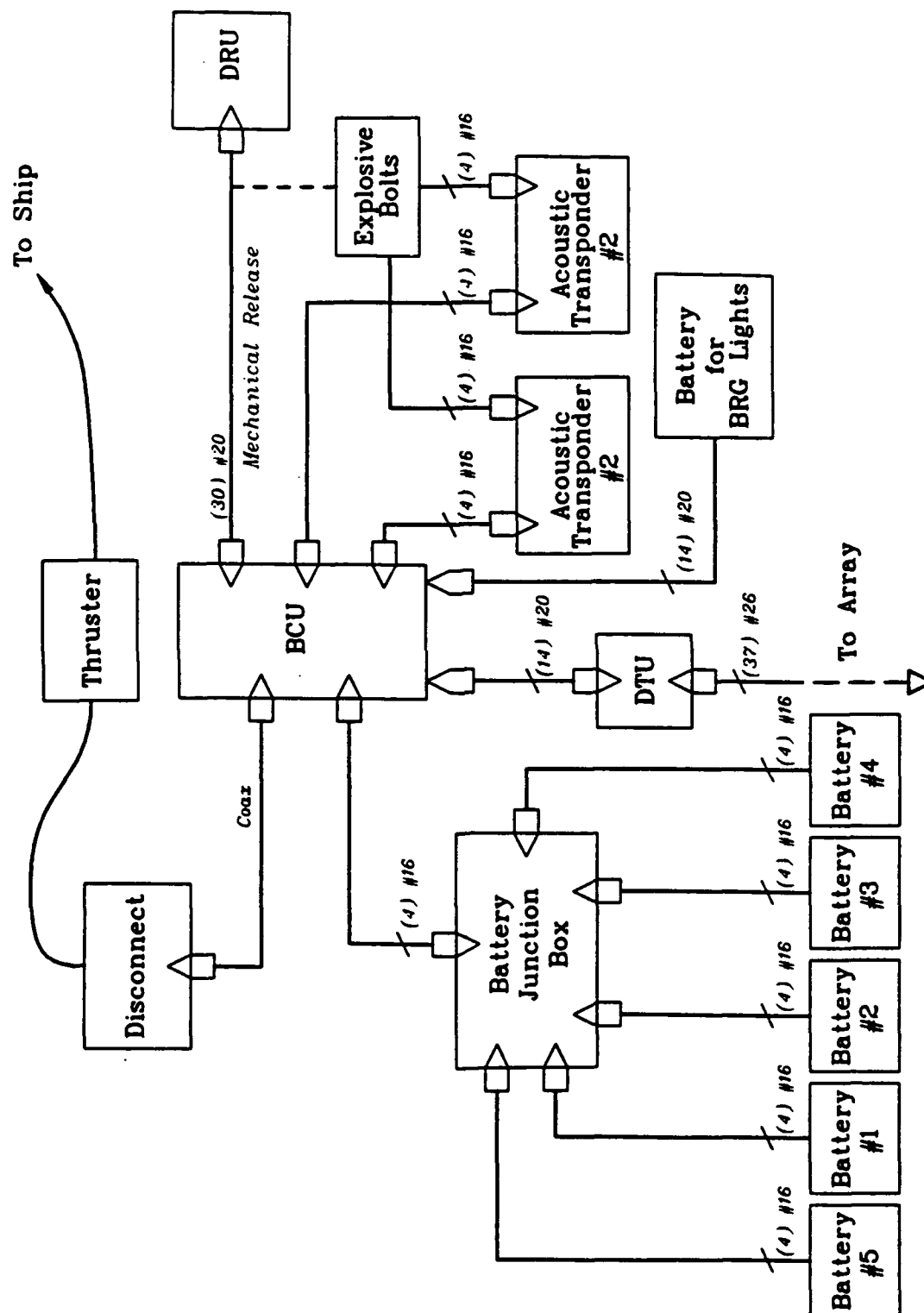


Figure 3.2-3. This wiring diagram summarizes the connections between the BIP mechanical components.

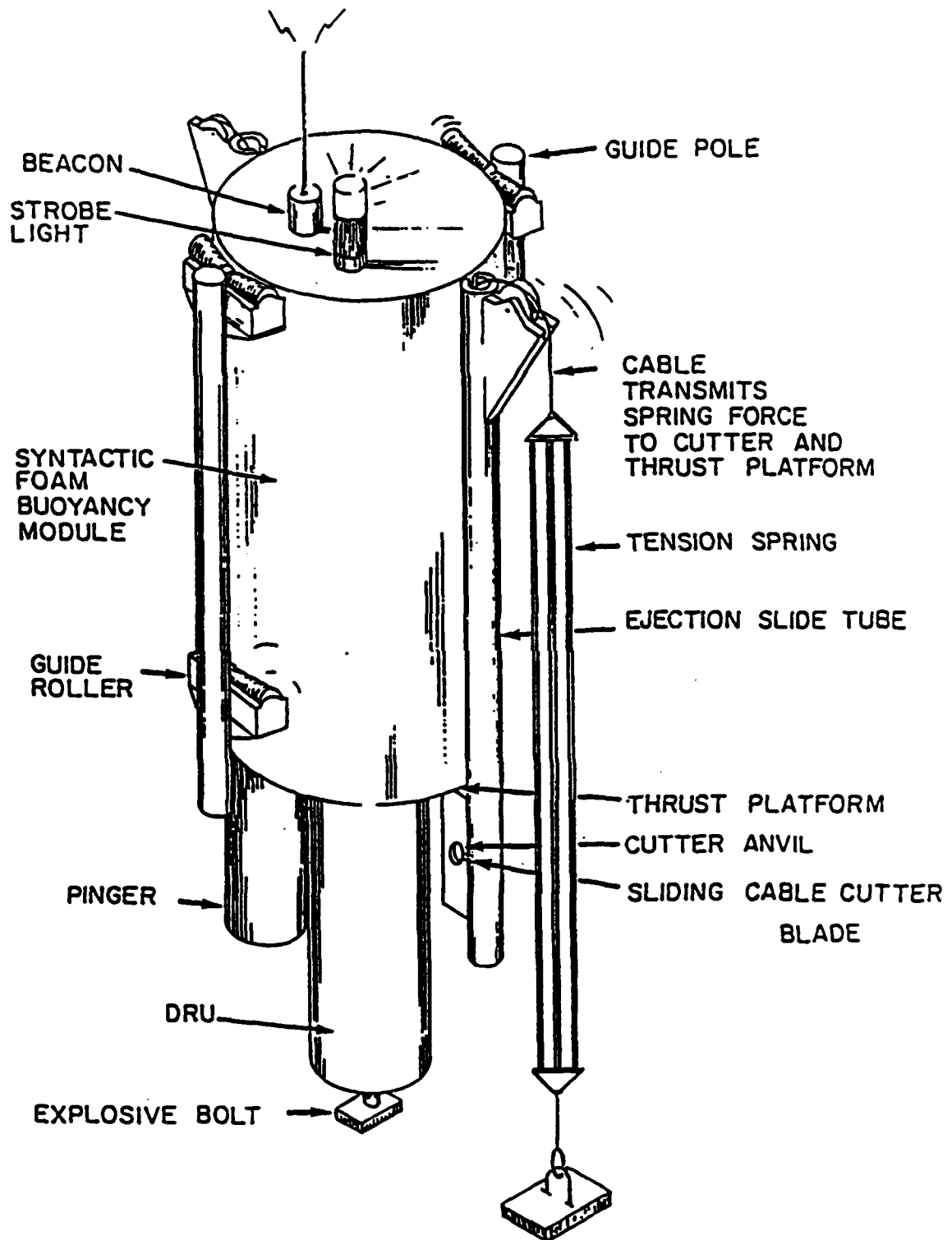


Figure 3.2-4. The Data Recording Unit (DRU), which contains all data recorded on the seafloor, is installed in a buoyant package which can be released if necessary from the BIP by acoustic command.

bottom of each transponder is replaced with a nine conductor bulkhead connection which connects the transponders to the BCU and the explosive bolts. The two transponders are mounted opposite each other on the inside of the BIP frame between the middle and upper rings.

The tether release is fabricated by Interocean System Inc. and was purchased by MPL/SIO. On either electrical command over the tether or on acoustic command via one of the two transponders, this device releases the tether from the top of the BIP. This action automatically places the BCU in autonomous seafloor operation mode. The unit is made of painted, anodized aluminum (7075-T6) and weighs 4.8kg(10.5lbs) in air. It is mounted on the top hub of the frame and connects the electromechanical soft tether, from the thruster, to the frame itself. The release mechanism is driven by a DC motor located in a pressure compensated, oil-filled chamber. The motor torque unlatches the hook holding the cable and the hook opens (under tension) and releases the cable. The electrical connector between the BCU and the thruster simply separates. This unit has been rigorously tested at WHOI and successfully releases under a 3,636daN(8,000lbs) tensile load.

Six underwater batteries (Deep Sea Power and Light, 1987) provide the power to operate the BIP during re-entry procedures and autonomous seafloor operation. Five batteries are connected via the junction box to the BCU. The sixth battery is connected directly to the underwater television camera (provided by MPL/SIO). Each unit consists of an oil compensated lead acid battery contained in a molded polyethylene box and provides 24 Volts for 38Amp-hours. The batteries are rated for full ocean depth (6,000m) and operate at seafloor temperature with a 15% loss in power. Each battery weighs 10.4kg(23lbs) in air and 9.5kg(21lbs) in water. The batteries are mounted on the fiberglass grating which extends over the lower ring of the frame.

The junction box connects the five batteries to the BCU. The box contains diodes to prevent accidental shorts from damaging the BCU or draining power from the other batteries. The pressure housing is made of anodized aluminum (7075-T6) and has an outside diameter of 191mm(7.5inch), an inside diameter of 152mm(6.0inch) and a length of 445mm(17.5inch). The weight in air is 11.3kg(25lbs) and the unit is 1.8kg(4.0lbs) buoyant in water. Five bulkhead connectors are mounted on one end cap and connect to the battery pigtails. The other end cap has one three conductor bulkhead connector leading to the BCU.

The fully loaded weight of the BIP is 1,466kg(3,232lbs) in air and 428kg(943lbs) in water.

3.3 CONTROL FUNCTIONS

The subsea computer in the BCU controls the sequence of events for all activities in SEABASS (Figures 3.3-1 and 3.3-2). The processor for the BCU is a low power CMOS version of a PC/XT using an 80C88 processor chip (Prada, 1988). The operating system is ROM based MS-DOS.

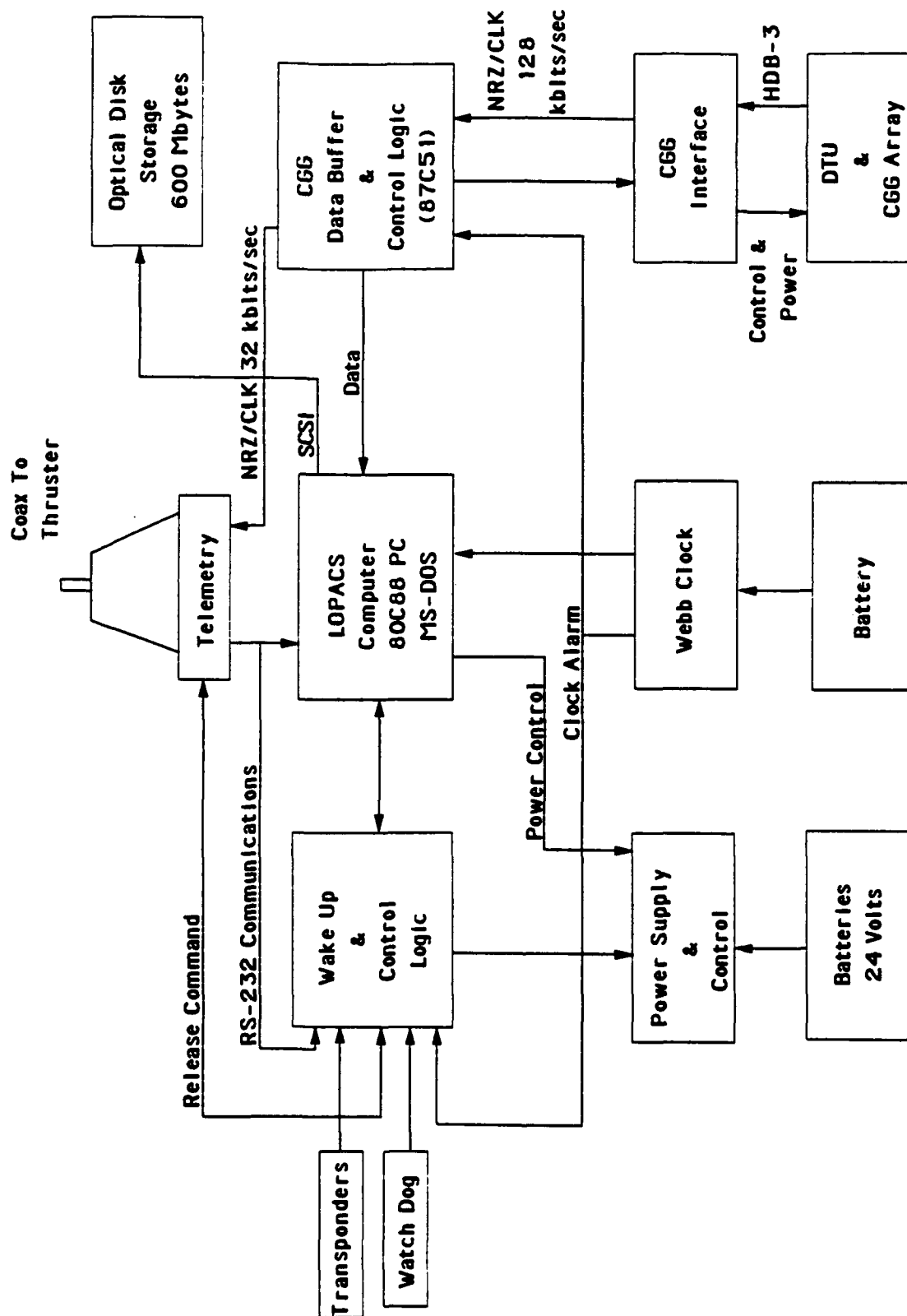


Figure 3.3-1. This block diagram summarizes the electronic components of the BIP. The watchdog, wake-up and control logic, LOPACS computer, Webb clock, CGG interface, CGG data buffer and control logic and the telemetry unit are contained in the Bottom Control Unit housing.

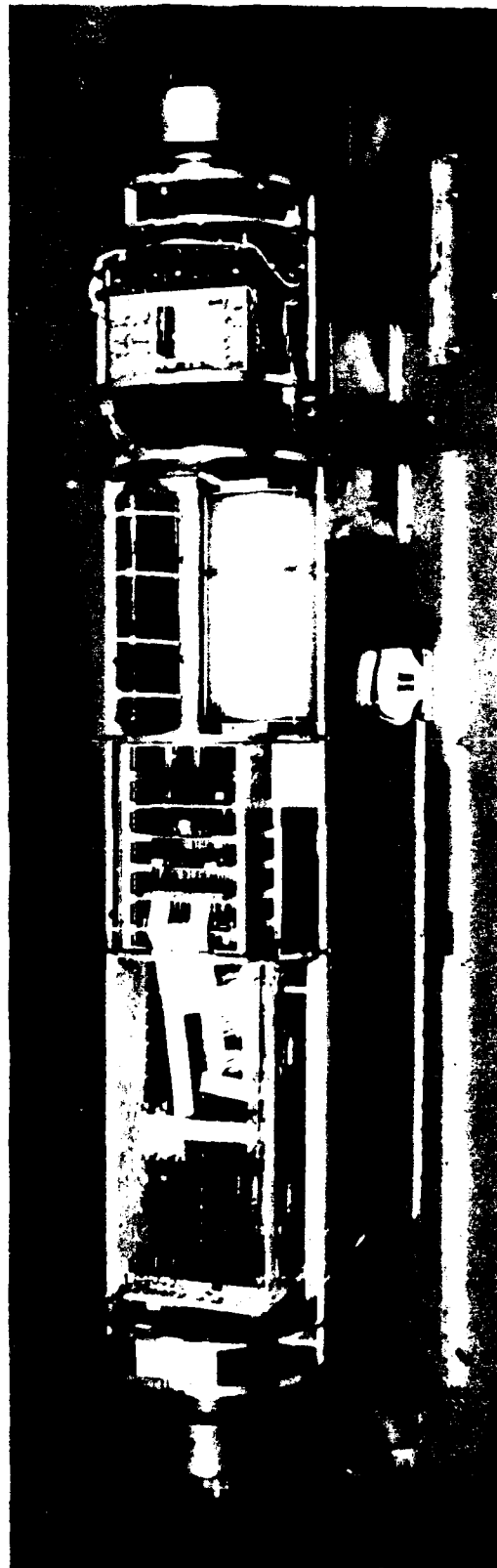


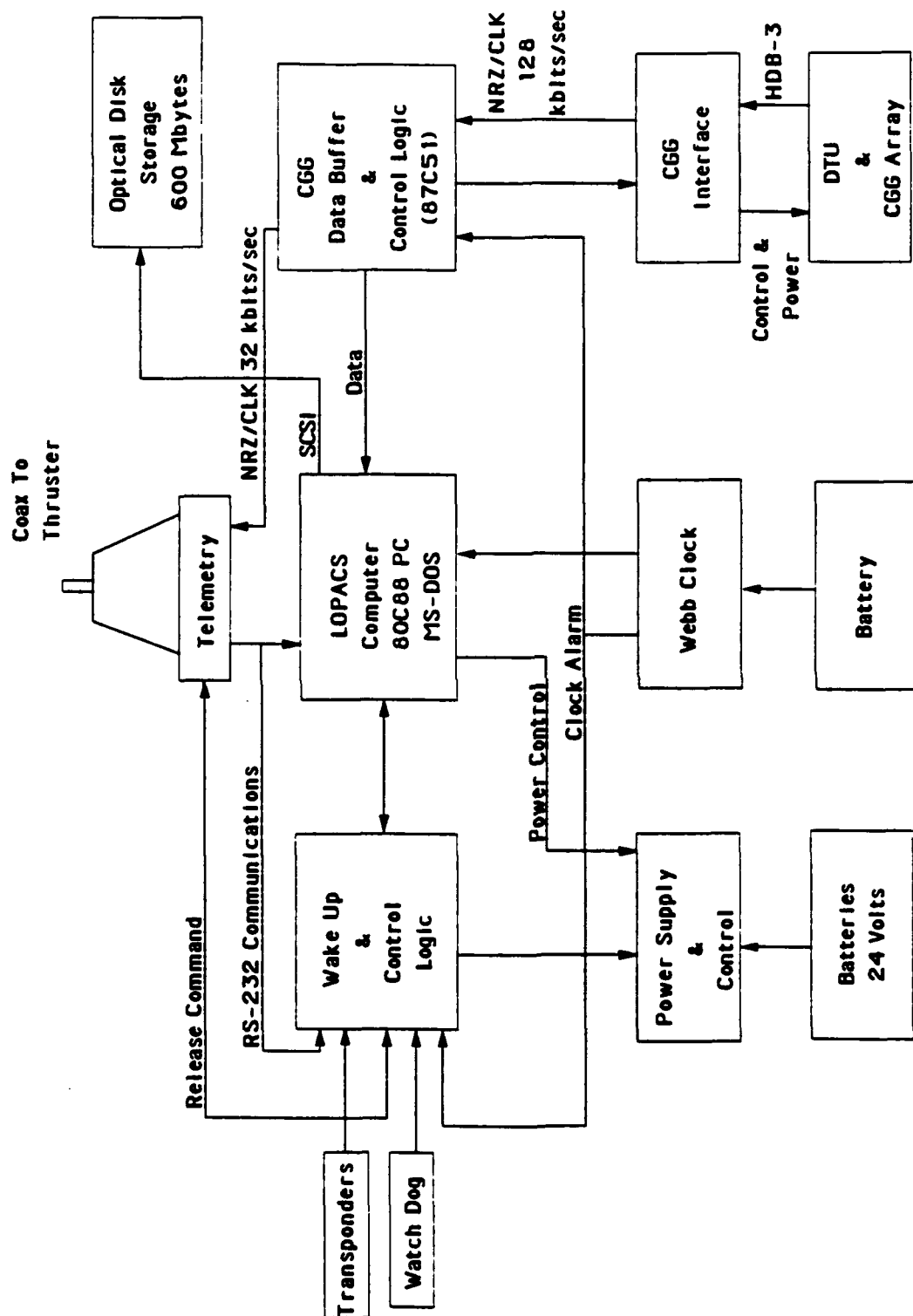
Figure 3.3-2. This photograph shows the BCU electronics.

To conserve power in the seafloor batteries during the autonomous portion of a deployment, all of the electronics in SEABASS is turned off between data acquisition intervals except for a low power 'Watchdog and Wake Up' circuit. Five events can trigger the circuit to turn on the SEABASS electronics (Figure 3.3-3): i) SEABASS is always turned on if power is being supplied from the surface ship either via the coaxial tether or a shipboard umbilical (MPL Power Detect). ii) In the event that shipboard power is not available, but the telemetry link is still active, SEABASS turns on when any signals are received on the telemetry link (Command Link Sense). iii) An acoustic command to one of two transponders mounted on the BIP activates SEABASS and initiates a data acquisition interval (Transponder). iv) An alarm signal from the main BCU clock wakes up the electronics. (For LFASE the main BCU clock was programmed to set off an alarm every 2 hours to trigger a 6 minute data acquisition interval.) v) A 'bark' from the 'watchdog' circuit wakes up the electronics.

On a wake-up signal, power is applied to the BCU computer. It 'boots-up' in MS-DOS and runs a start-up file which executes the BCU program (Figure 3.3-4). The BCU program polls the wake-up circuitry to determine under what circumstances it was woken and performs the appropriate action. For example, if, after a communications 'wake up', a check of the power supply confirms the presence of telemetry power (from the surface), it is assumed that the shipboard operator caused the 'wake up' and wants to issue a command. The computer then waits at the program prompt. If, on the other hand, the clock alarm caused the 'wake up' and a check of the power supply confirms that the telemetry power is off, it is assumed that SEABASS is in 'seafloor recording mode' and a data record is acquired and recorded on the DRU. When finished the computer resets the main clock alarm and turns itself off.

The 'watchdog' circuit (Figure 3.3-3) attempts to correct any problems that occur if the system fails to respond, 'hangs-up', or misses a normal 'wake up'. This circuit consists of simple clock and logic circuitry and runs off the main power. The 'watchdog' is 'fed' (that is, the counter is reset) by the computer at the start of every acquisition interval and it is set 'to bark' (that is, issue a wake-up) 130 minutes after being fed. (The 130 minutes is 10 minutes longer than the longest scheduled 'wake up'.) If the system is functioning correctly a 'wake up' will always occur in less than 130 minutes. If a problem occurs and the 'watchdog' is not fed for 130 minutes it will issue its own wake-up. Before issuing the 'wake up' flag, the 'watchdog' removes power from all electronics for five seconds. When the 'wake up' flag is issued, the computer reboots, checks its memory for the next scheduled acquisition, sets the clock alarm, and goes back to sleep.

There are five ways to initiate a data acquisition interval: i) A background recording schedule is programmed directly into software to acquire a six minute record every two hours. ii) The user can specify up to two hundred and fifty-six special 'wake up' times and durations which are stored in Electrically Erasable Programmable Read Only Memory (EEPROM). This schedule can be loaded or changed at any time prior to terminating the telemetry link. iii) An acoustic command initiates a one hour recording window. iv) During shipboard recording arbitrary start times and durations of an acquisition interval can be entered from the surface. v) Also during shipboard recording, a standard pulse test of the array (as described in Section 2.3) can be activated.



Bottom Instrument Package

Figure 3.3-3. To conserve power in seafloor recording mode the computer is only on when data are being acquired or written to disk. Five conditions can turn the computer on: a signal from the watchdog circuit, a signal from the acoustic transponder, power supplied from the surface, a signal from the main BCU (or Webb) clock, or a telemetry command. The watchdog monitors the computer and restarts it if the computer 'hangs up'.

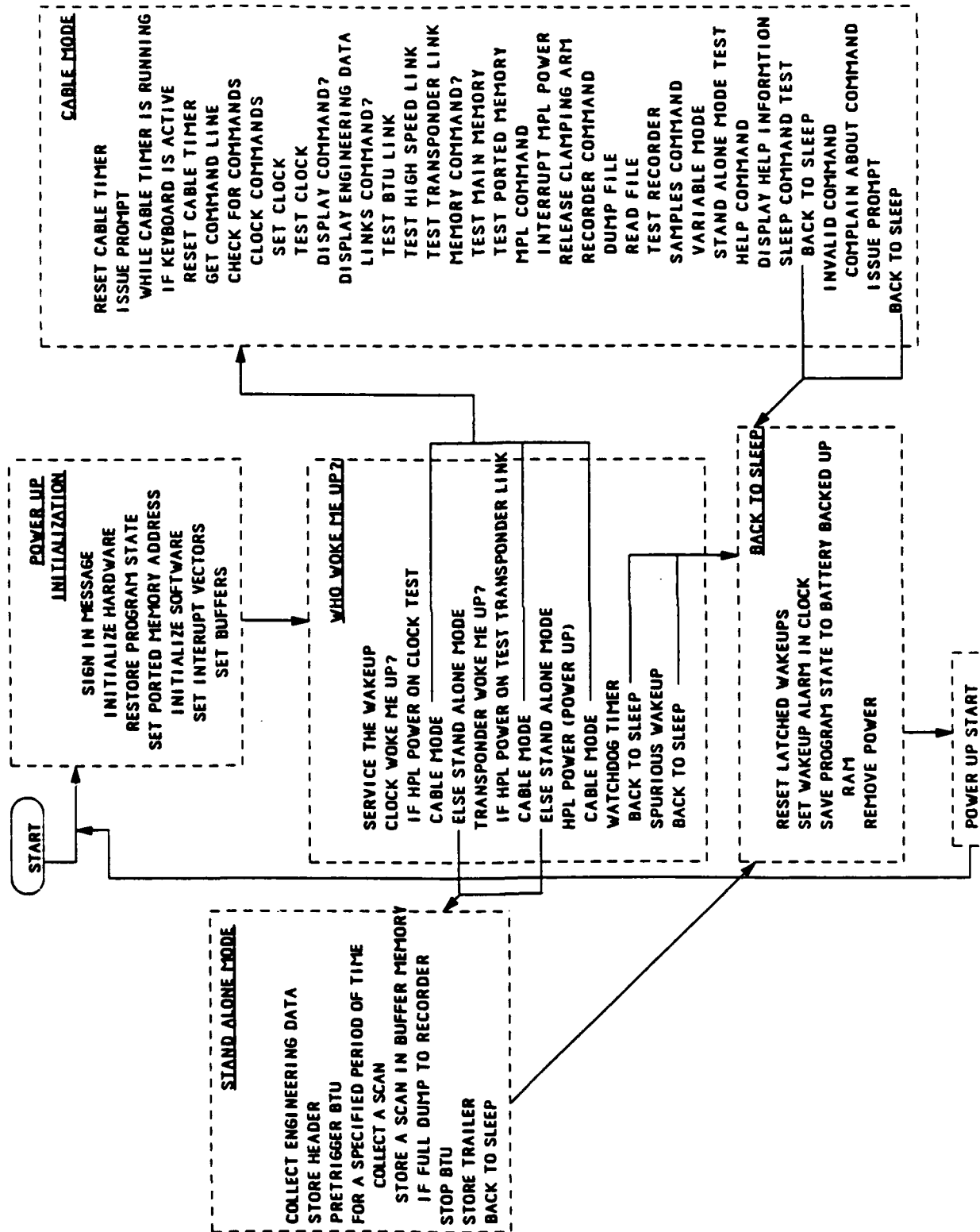


Figure 3.3-4. The BCU software flow chart summarizes the control functions carried out by the seafloor computer.

To release the clamping arms on the four satellites, 100VDC at 2.4 amps is applied for 20 seconds to the solenoids in each satellite. For seafloor operation this trigger signal is applied from the surface over the same line as the 28 volt power supply. Prior to the trigger signal being applied, and on command from the surface, the BCU and CIEM electronics switch to battery supplied power and the 28V power supply line is connected to the solenoid release line in the CGG cable. After the trigger signal is applied the BCU and CIEM electronics are switched back to the 28 volt power supply line.

3.4 CLOCKS AND TIMING

SEABASS, in seafloor recording mode, requires accurate timing in order to monitor events, such as earthquakes, and to acquire seismic refraction profiles. In event monitoring, events are identified by the absolute time (in Universal Standard Time (UST) to an accuracy of one second) at which they occur. In seismic refraction profiles absolute time to the same accuracy is required to obtain ranges and bearings from the navigation data of the shooting ship. Also very accurate relative times from the shot to the receivers (to within 20msec) are required to measure meaningful velocities and depths for studying earth structure. In both applications, advanced array processing of the digital data requires extremely accurate (to within 50µsec) relative times between samples on adjacent channels.

Three timing devices are used in a SEABASS deployment. i) An oscillator in the DTU controls the digitizing process of the twelve channels from the borehole array (see Section 2.3). Very accurate relative times are obtained. ii) Absolute 'instrument' time for the recorded data is provided by a Webb Research high precision clock (Webb Research, 1989) mounted in the Bottom Control Unit. This is the time that is written on all seismic data records in the BCU and on-board ship. iii) Instrument time is referenced to Universal Standard Time by calibrating the BCU clock with time from a GOES satellite. Peal (1991) has shown that discrepancies between GOES and WWV times are caused by diurnal variations in the satellite location. After appropriate corrections accuracies of 100-200µsec are possible. (At-sea tests prior to Peal's study indicated that GOES, as received on a Kinometrics Truetime Clock (Kinometrics, 1986), gives Universal Standard Time, as received on WWV and SATNAV, with an accuracy of ±1.6msec.)

The BCU clock is a high stability time base and clock that outputs time on command like an alarm clock. An external command tells the clock to an even second when to issue the alarm. When the time occurs the clock outputs an @ character. The leading edge of the @ character has a resolution of less than 1µsec. If the aging and temperature drifts of the BCU clock and DTU sampling rate oscillators are taken into consideration, we can measure GOES/UST time to 1msec.

It is not possible to time tag an asynchronous data stream with this system. However, it is possible to use the clock alarm to initiate an event. In SEABASS, the scan data from the DTU are initiated and terminated by the BCU clock alarm. The start time of a data

file is known to the accuracy of the BCU clock. The last scan in a file occurs within one sample (± 4.0 msec) of the termination time. These times are written in a trailer record on the disk and provide a check on drift of the DTU oscillator (used in the digitizer) over the duration of the recording window. Since the scans are numbered and the DTU oscillator is well calibrated, it is possible to know the absolute time (GOES/UST) of any sample to an accuracy of ± 1 msec and the accuracy of a seismic event in the data to ± 5 msec.

The BCU clock can be calibrated with the GOES satellite clock either through an umbilical to the BIP, for shipboard calibration, or over the data telemetry link, for seafloor calibration. For clock calibration the data channel is dedicated to transmitting time strobes. The operator on the surface commands the BCU clock to issue an alarm at a given time in the future (the next even minute is generally used). This 'hack' is received instantaneously at the surface where it latches the time on the GOES clock. The two values are displayed and the time offset is determined.

During the shipboard recording phase the BCU clock is calibrated on a regular basis to check the offset and drift while the unit is on the seafloor. This is particularly important since clock drift can be quite dramatic due to the temperature change from the deck (about 25°C) to the seafloor (about 0°C). As soon as the BIP is recovered after the seafloor recording stage a calibration is made on deck over the umbilical. Clock offset and drift during the autonomous operation can then be established. The calibration factor is applied during the data reduction stage (Section 3.10) so that all times in the laboratory (and data exchange) format are absolute GOES/UST times.

3.5 SEAFLOOR PROCESSING AND TELEMETRY

The BCU receives a 128kbit/sec serial bit stream in HDB3 format from the DTU, corresponding to the 12 geophone (or 11 geophone plus hydrophone) channels sampled at 2msec plus the auxilliary channel data (Figure 3.3-1). The contents of the serial bit stream, in CGG format, are defined in Figure 3.5-1. (HDB3 format is a 'French Post Office Code' telemetry format defined in Boulvin (1974). CGG format refers to the definition of the words and bits within a scan. A12G4 format, discussed further in Section 4.5, is the field format of data from the digitizer.) The 2msec sampling rate provides more data than can be conveniently stored in the BCU buffers and DRU and the transmission rate of 128kbit/sec exceeds the allocated bandwidth of the telemetry system to the surface. In addition the frequency band of the system (2-50Hz) does not require such fine sampling. The data stream is therefore subsampled every fourth sample, resulting in an acceptable transmission rate of 32kbit/sec and an acceptable data volume. At this rate each data channel is sampled 125 times per second.

Each scan contains one sample of an auxilliary channel (Figure 3.5-1). It takes eight scans to deliver information from all auxilliary channels. If every fourth scan (or time sample) was simply taken from the CGG format data stream, data from only two auxilliary channels would be retained. The proper stream of auxilliary channel information is preserved by reformatting data in the BCU. The bit stream from the DTU is converted from HDB3 format

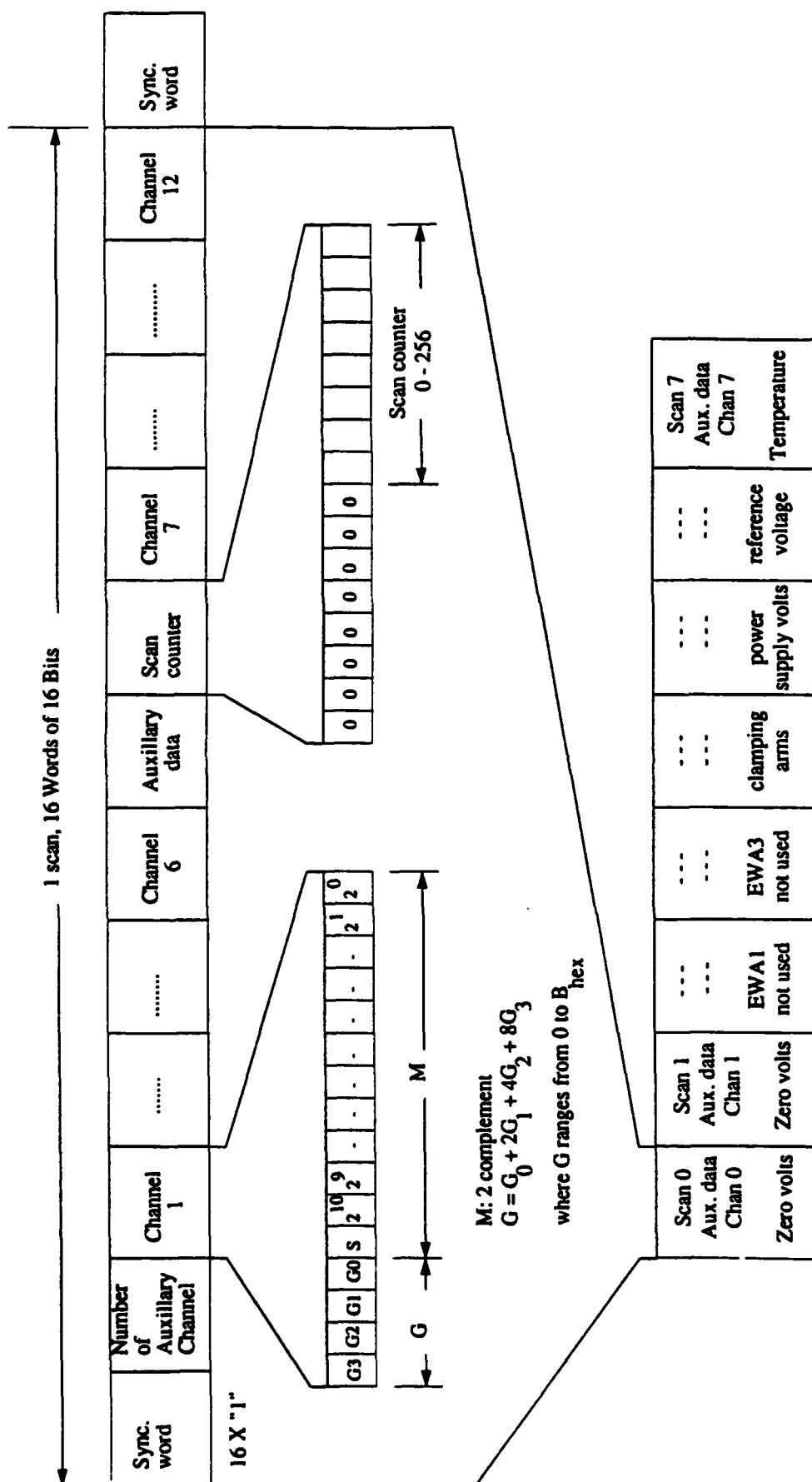


Figure 3.5-1. A scan of data is generated by the DTU 500 times per second. Every fourth scan is recorded as described in the text. Each scan has 16 words of 16 bits each. The first word is a 'Sync' word which identifies the start of the scan. The second word contains the number of the auxiliary channel (1-8) which is displayed in this scan. Words 3 through 8 contain the data in A 12G4 format for the first six channels. The ninth word contains the auxiliary channel data. The tenth word contains the scan number which is used in postprocessing to check that no scans have been dropped in the telemetry or recording process. Words 11 through 16 contain the data in the last twelve channels.

to 'Non Return to Zero (NRZ) plus clock' format and passed to a data buffer where the subsampling by four takes place. (NRZ plus clock is an electronic format for the digital data stream.) Hardware logic contained in an Altera EPLD synchronizes to the CGG data scan and converts it to 8 bit parallel format. An 87C51 microcontroller reads the scan, stores the auxilliary channel data and address, and then reassembles a new scan in CGG format but at one fourth the rate. The new scan is passed back to the EPLD where it is synchronously clocked out at 32kbit/sec. The eight channels of auxilliary data, which appear in turn every eight scans will thus rotate properly even though the number of scans has been reduced by a factor of four. Whenever the DTU is active, serial output from the EPLD in the CGG data buffer and control logic (Figure 3.3-1) is sent to the telemetry module (part of the CIEM) for transmission to the surface.

The microcontroller (on the seafloor) also numbers each scan by placing a counter in the one unused 16 bit data word. The data reduction system ashore reads this 'scan counter' to detect any data drop outs that may have occurred in the telemetry, recording, or data transcription stages.

In addition, parallel scan data from the 87C51 is fed to the subsea computer in the BCU at an 8msec rate. Every acquired scan, whether intended for shipboard or seafloor recording, is read by the subsea computer and checked for correct length and sequencing of the auxilliary channel addresses. The subsea computer counts the number of correct scans and appends this number in a trailer to the data stream as quality control information.

If remote acquisition has been requested, the scan data gets no further than the input buffer in the subsea computer. If local recording has been requested the data is buffered into blocks for transmission to the Data Recording Unit.

The data is telemetered over a coaxial cable in the tether, through the thruster, and over the 0.68" coaxial cable to the surface. A communication and interface electronic module (CIEM), designed and supplied by MPL/SIO, is mounted in the BCU housing. This module is powered from the thruster except when the 'Arm Release' command is given, when it is powered by a 24V main battery supply. The CIEM is connected to the surface ship via the coaxial cable from the tether. The CIEM supports: i) The video/power and engineering data channels to the BRG. These signals, which are necessary for the re-entry function, are carried on two twisted pairs from the BCU to the BRG, and totally by-pass all of the SEABASS electronics. ii) A full duplex 2400baud telemetry link for BCU communications. iii) A high speed (32kbit/sec) one-way data link (NRZ plus clock) to transmit the seismic data to the ship. iv) A 28V power supply line that it is also used to trigger the 'Arm Release' when the command is given.

3.6 SHIPBOARD RECORDING

There are two telemetry channels between the surface ship and the BIP: a one-way, high bandwidth (32kbit/sec) channel for the digital data stream and a two-way, low speed channel (2400baud) to pass commands to the BCU and receive state-of-health and timing information.

A PC/AT desktop computer on board the host vessel is used as a terminal to the BCU computer and as a recording system for the high bandwidth data telemetry channel (Figure 3.6-1). A second PC/XT computer is connected to the same communications line as the PC/AT to act as a 'spy' on the inter-processor communications during data acquisition.

A data buffer, functionally similar to the one deployed in the BCU, is installed in the backplane of the PC/AT. A laboratory version of the Mountain Optech optical disk drive (Optotech, 1987) records the seismic data on board ship in the same format as the recorders in the DRU. Disks recorded on one system are interchangeable with the other system. Regardless of the acquisition interval the data stream is telemetered in real time to the surface and recorded continuously.

The digital data stream is also passed in real time to the Multilock Interface Unit (IU). All of the state-of-health and quicklook functions described in Section 2.4 are available in the Interface Unit. DTU tests, initiated in the BCU, can be analysed and displayed on the IU. Hard copies of the IU screen information can be acquired by a Polaroid camera. The IU also demultiplexes the data stream and converts the twelve digital seismic channels to analog signals for display on an oscilloscope and an oscillographic recorder. Displaying the analog signals in the ship's laboratory makes it possible to make real time decisions on the shooting program and provides positive confirmation that the shots are being received and acquired properly.

A Kinometrics Truetime GOES referenced clock (Kinometrics, 1986) provides the official time for the experiment. The clock in the BCU is referenced to the GOES time using the procedure described in Section 3.4.

3.7 SEAFLOOR RECORDING

Three Mountain Optech optical drives (Mountain Optech, 1988) are mounted in the DRU (Figure 3.7-1). They are connected in parallel to the subsea computer through a standard SCSI host adaptor card. Each disk holds 200Mbytes of data for a total of 600Mbytes. This corresponds to about 41hrs of data. The drives are mounted in shock resistant housings and operate in any orientation and at temperatures well below 0°C. (The Mountain Optech optical disk drives were about twice the cost and had about a tenth of the storage capacity of an alternative 8mm tape cartridge recorder (Exabyte, 1987) that was available at the time of construction (summer 1988). However the tape drive required much more power (partly due to rewinding the tape after recording intervals), the magnetic tape media was only guaranteed down to 5°C (which is above ocean bottom temperature), and the tape recorder had not been

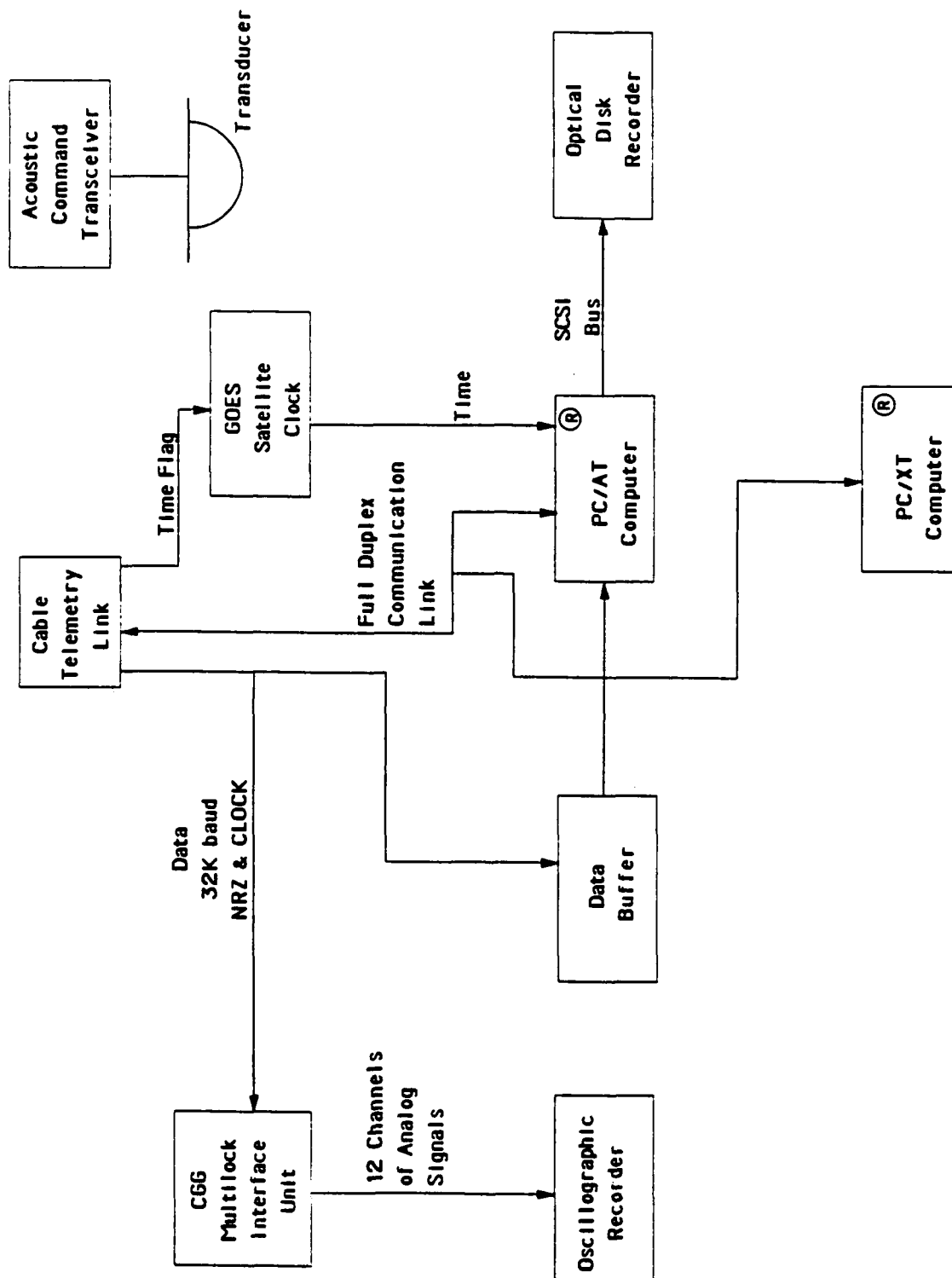


Figure 3.6-1. This block diagram summarizes the shipboard control and recording equipment.



Figure 3.7-1. This photograph shows the three optical disk recorders and the power supply and interface electronics in the DRU module.

designed or tested for hostile environment operations. For LFASE we chose the optical disk drives. However, because the interface to the drives is standard, we can change to tape drives if necessary when their limitations have been overcome.)

There are three ways that a data acquisition interval can be implemented. i) A fixed interval and duration is written into the control software prior to loading it on EPROM. This will ensure a minimum, background recording program whenever the BCU computer is operational. On LFASE these 'hardwired' values were set to acquire a 6min record every 2hours. ii) In addition to this 'background' recording window, and over-riding it if necessary, up to 256 special windows can be defined. These are stored on EEPROM (Section 3.3) as a start time and a duration. iii) Also, on acoustic command, via the acoustic transponders mounted on the BIP, a recording window can be initiated with a one hour duration. In the event that the tether is disconnected from the BIP prematurely this permits the receiving ship or the shooting ship to activate a large window in which to collect controlled source data.

For acquisition intervals of six minutes or less, the data is stored on RAM during the interval and dumped to optical disk after the data has been acquired. For intervals longer than six minutes the data is only buffered on RAM and is written continuously to optical disk throughout the recording window. (During seafloor recording on LFASE, mechanical noise from the optical disk recorder was observed on the borehole sensors. So acquisitions taken over intervals six minutes or less did not show the recorder noise and were of slightly better quality than the longer records.)

3.8 POWER CONSUMPTION

Power consumption of SEABASS can be considered in four parts. The clock and wake-up circuits, which are active when the BIP is 'asleep', only draw 3mamps. The CPU computer in stand-by mode draws 380mamps. The DTU, which runs during data acquisition intervals, draws 340mamps. The DRU recorders, which run while data is being written to the optical disks, draw 1.07amps. All systems run at 24V.

There are two recording modes. Up to 2Mbytes (approximately 6min of data) can be acquired on RAM during the acquisition interval and written to disk after the acquisition. (In this mode the mechanical noise from the recorder does not contaminate the seismic data.) The data transfer rate to the recorder is six times as fast as the data acquisition rate. So if the whole 41hrs of recording capacity was acquired in this mode (for example in 6min windows) the CPU and DTU would run for 41hrs and the CPU and DRU would run for an additional 6.8hrs. If we assume that the system must operate autonomously on the seafloor for 2 months the BIP will be asleep for another 1500hrs. So 0.71KWH are used to acquire data, 0.24KWH are used to write the data to disk and 0.11KWH are consumed while the BIP is 'asleep'. Total consumption in this mode is 1.06KWH.

In the second mode data is written to disk as it is being acquired. The CPU, DTU and DRU, which together consume 1.8amps, run for the full 41hrs. Power consumption for acquisition and recording is 1.77KWH. Total consumption allowing for two months on the seafloor is 1.88KWH.

In an actual deployment such as LFASE the acquisition intervals vary between the two modes. Windows less than 6min are scheduled to extend the total observation period. Longer windows, up to an hour, are acquired to get good statistics for the low frequency energy. Additional power is also required if the system malfunctions or if the BCU must search the recorders for available space prior to writing a file.

After the tether is disconnected, power is supplied from batteries (Deep Sea Power and Light, 1987) mounted on the BIP. Each battery provides 38Amp-hours at 24V at room temperature when it is new and freshly charged. This is de-rated by 15% for operation at 0°C and by 2%/month for the 'shelf life'. So the power capacity of a new battery at room temperature is reduced to 80% for a two month seafloor operation. For estimating the number of batteries required for a deployment we assume that each battery will provide 0.73KWH.

For the worst case, where acquisition and recording occur simultaneously (1.88KWH), SEABASS requires at least three batteries. On LFASE two additional batteries were used to allow for a safety factor in case a whole battery failed and to provide extra power in the case of subsystem malfunctions.

The BCU clock and acoustic transponders have their own independent power supplies (see Section 7.11).

3.9 QUICKLOOK SHIPBOARD PROCESSING

The shipboard components of SEABASS provide four ways that we can check data quality in real time or near-real time while in tethered mode. The data stream from the BIP passes through the shipboard microcomputer (PC/AT) to an optical disk recorder (in the same format as the seafloor recorders) and also to the Multilock Interface Unit (IU). In the interface unit the data is demultiplexed and passed through a digital-to-analog converter (DAC) which allows all twelve channels to be displayed on an oscillographic recorder. During an airgun shooting run for example, SEABASS would be set to acquire a long (say one hour) data interval. During this interval the data stream to the surface is continuous and a large continuous file is acquired on the optical disk. The output of the DAC is twelve continuous analog channels. Just prior to a shot the oscillographic recorder is started and the energy arriving at the borehole array from the shot can be observed on all twelve channels on the recorder paper.

Any two channels of the output of the DAC can also be sent for display to an oscilloscope. The oscilloscope displays data whenever a data stream is being acquired from the seafloor.

The SEABASS data, which is demultiplexed in the IU, can be processed and displayed in the same fashion as data from the basic Multilock. All the functions of the IU which are described in Section 2.4 can be carried out and displayed on the IU screen. These include state-of-health information as well as processing of the seismic signals. Hard copies of the IU screen are obtained with a Polaroid camera.

In order to check that data is being recorded correctly on the optical disk we have a separate Quicklook System (QLS) in the lab based on a third PC/AT with its own optical disk recorder and dot-matrix printer. After an acquisition interval the optical disk can be physically transferred from the SEABASS optical disk recorder to the Quicklook System. A software package called SEASHOW has been written to read data from the optical disk and to display it in a variety of formats on the PC/AT screen and/or printer. Time series data over any interval and on any number of channels can be displayed in engineering units (Volts on output). A second software package called CGGEDIT checks the optical disk files for scan count errors (Section 7.8) and read errors. CGGEDIT also has a capability for editing corrupted files. While in tethered mode during a shooting program, disks can be checked on the Quicklook System as soon as they are full and back-up copies of the field data can be made while other data is still being acquired. The Quicklook System is particularly convenient for generating figures for the Shipboard Report.

3.10 POSTDEPLOYMENT PROCESSING

SEABASS acquires both ambient noise and controlled source (airguns and explosives) seismic records from below the seafloor. Post deployment processing of SEABASS data consists of six general tasks. i) It checks the data quality (for scan count errors, read errors, clipped or overloaded values, etc). ii) It converts all the data from field format to a convenient laboratory format, for storage and processing, and to an exchange format, for distribution to other labs participating in the experiment. iii) It generates acquisition summaries in terms of RMS signal levels for the whole experiment. iv) It computes spectra, coherence plots, and third octave band summaries of the ambient noise data and a limited amount of controlled source data. v) It generates record sections of the controlled source data and maps of the shooting lines. vi) It computes the orientation of the horizontal sensors based on polarization analysis of the controlled source data.

The processing is carried out on a microVAX computer system equipped with an optical disk recorder, a nine-track tape drive and a laser printer. The system is portable and it can be taken to sea (as on LFASE) or to the field so that advanced processing can be carried out quickly after the experiment. An overview of the post deployment processing used on LFASE is given by Little *et al* (1990a) and Bolmer *et al* (1991).

Each time sample of the twelve SEABASS channels is tagged with a sequential number, the scan count, in the BCU on the seafloor. Confirmation that all the data is being telemetered and recorded correctly is made by checking these numbers on the microVAX. Occasionally there are gaps in the data as read on the microVAX that are not observed when

the data is read on the Quicklook System. These gaps are recovered by copying the file to a new optical disk on the Quicklook System and then recopying the file from the new disk to the microVAX. Scans that are truly missing even on the primary field disks are replaced with zero and noted in a log file. Replacing the scans with zeroes keeps the timing information (which is done by counting scans) correct for the remainder of the file. The data is also checked for the maximum and minimum values output from the digitizer (Section 4.5). The presence of these values, which is noted in a log file, indicates overloading or clipping in the acquisition system. Analysis of files which contain genuine scan count errors and/or clipped values is carried out with caution.

In SEABASS the data are recorded in the field in CGG A12G4 format (see Section 4.5). A more convenient format for in-house processing and data exchange is ROSE format (Section 4.5). This format was developed as an exchange format for marine seismic experiments in which both ambient noise and controlled source files were acquired. The software for data transcription from A12G4 to ROSE is described in Little *et al* (1990b). When SEABASS is used in VSP mode, as in the Michigan borehole test (Section 6.6), the exchange format is SEG-Y (Barry *et al*, 1975), which is widely used in the petroleum exploration industry.

A convenient way to summarize the data is to plot the root-mean-square (RMS) value in decibels (dB) for a given window length (for example, 10secs) and interval (for example, 60secs) for channel 1 (the vertical component of the top satellite) for all of the data acquired during the experiment as a function of time (Figure 3.10-1). On the same figure we show when the explosive and airgun sources were fired, when other seismometers in the experiment were recording and when earthquakes occurred that may have been detectable. This display is quite useful in assessing the amount of data acquired in each phase of an experiment, identifying interesting time intervals and in determining quiet ambient noise periods.

In order to reduce large quantities of ambient noise data to a manageable size we reduce whole spectra to six numbers representing the average power spectral density in third octave bands centered at 1, 2, 4, 8, 16, and 32 Hz and plot these, for various subsets of the twelve channels, as a function of time during the deployment (Figure 3.10-2). This type of plot contains frequency information which is not available in the RMS summaries and it is easy to compare noise levels between different sensors. Similar plots are generated to display the coherence (or cross correlation) between sensors.

Record sections of controlled source data (airguns or explosives) are used to study the structure of the sediments and upper crust and to identify the prominent energy paths contributing to transmission loss curves. (An example of a record section from LFASE is shown later in Figure 6.8-3.) Record sections require accurate timing and navigation between the shooting system and the receiving system. All clocks are corrected, for both offset and drift, to GOES satellite time and navigation of the shot locations is determined using LORAN

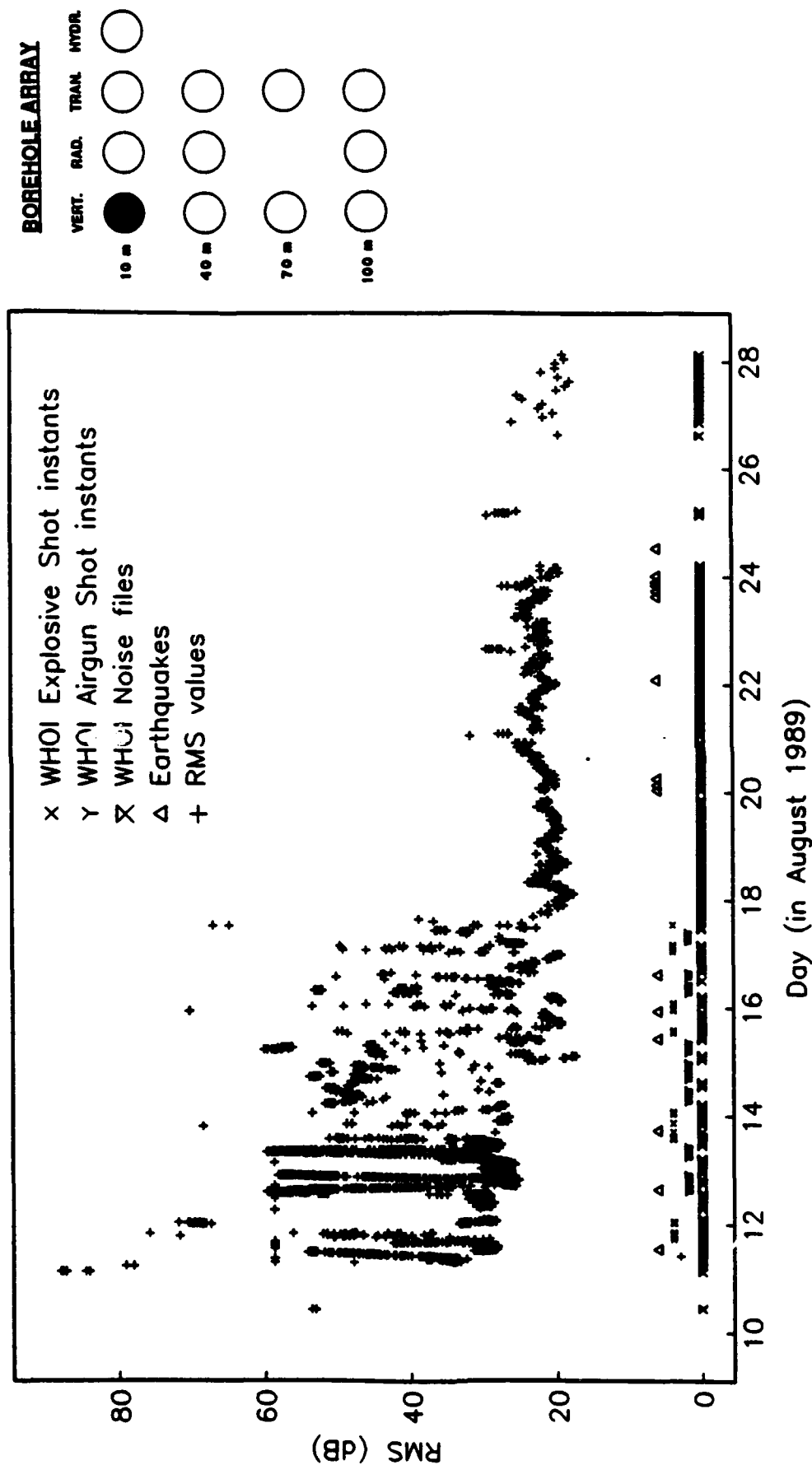


Figure 3.10-1. RMS levels of the vertical channel in the top node for 10sec windows every minute throughout the data set are a convenient way to summarize levels in the experiment. The peak levels (over 50dB) on days 10-18 are due to the shooting program. In windows between shooting there is ship noise from the USNS Lynch and the R/V Melville. After day 18 the two ships have left and the RMS levels show the variations in ambient noise. The peaks after day 18 are transient ships in the area. The symbols along the bottom of the figure show when explosive shots, airgun shots and earthquakes occurred during the experiment. No events associated with the earthquakes have been identified in the SEABASS data.

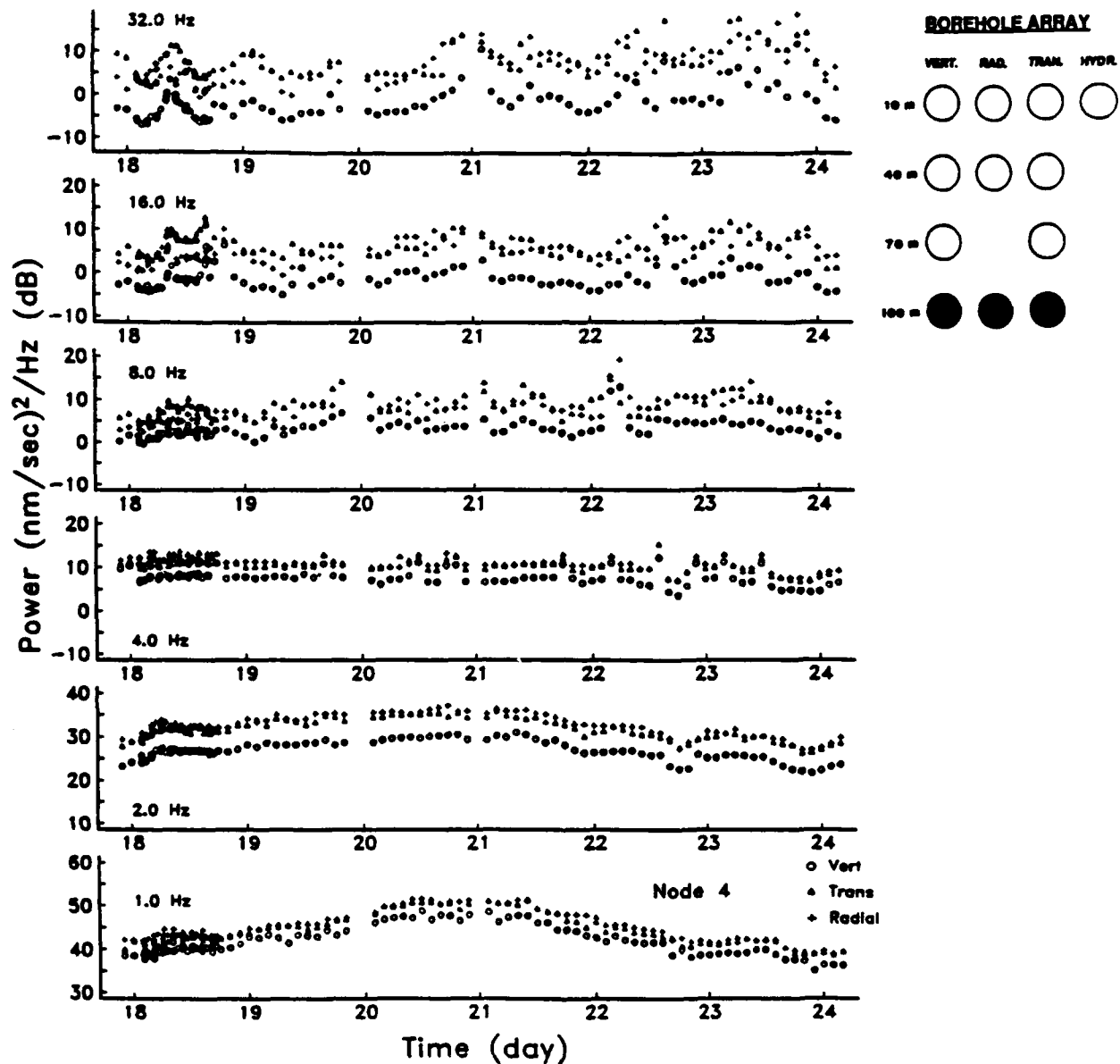


Figure 3.10-2. A convenient way to look at frequency dependent effects throughout time on a number of channels is to compute power levels in third octave bands. Spectra for this figure were computed for 5 minute contiguous windows. There is a broad rise and decline in noise levels at frequencies below 2.0 Hz at the bottom node which can be correlated with a passing storm. At higher frequencies significant noise level changes can occur on the vertical component without changes on the horizontal components. This has not been explained.

navigation. The resulting data is stored in the headers of the ROSE files and maps are made of the shot locations. Determining accurate relative times, ranges and azimuths for the shot data is the most time consuming aspect of data reduction.

The orientation of the horizontal sensors in SEABASS is determined from the polarization of the P-waves in the controlled source data. P-wave arrival times are picked from the record sections and shot azimuths are taken from the navigation data. Polarization plots of the seismic traces of the two horizontal channels (for example see Figure 6.8-5) are generated. The particle motion trajectories on the polarization plots should form a straight line which points at the shot location, so the angle between the shot azimuth and the horizontal components can be determined. By averaging these angles from plots for a large number of azimuths the geophone orientations can be determined to within a few degrees.

4. DESIGN CONSIDERATIONS AND SPECIFICATIONS

4.1 FIELD VALUES OF PRESSURE AND GROUND VELOCITY

At the time we designed SEABASS we did not have simultaneous pressure and ground velocity values for signals and ambient noise in the frequency range of interest in boreholes on the seafloor or on land. The test procedures we carried out in Marolles, in Michigan and at sea (see Sections 6.5, 6.6 and 6.8) have provided these values and they can be used for future designs.

Table 4.1-1 presents ambient noise and controlled source levels as one third octave band averages for frequencies from 2.0 to 32Hz. The data are based on a vertical geophone co-located (within 1.5m) with a borehole hydrophone. In the two land sites, Marolles and Michigan, the sensors are at 1540 and 50m depth respectively. At the seafloor (LFASE) site the sensors are at 10mBSF. In all tests the results displayed are acquired in cased holes.

Table 4.1-1 shows clearly that the ratio of pressure in a borehole to the vertical motion of the borehole wall in field units varies by almost 60dB depending on frequency, geographic location, depth in the well and signal type (ambient noise, airgun, land airgun, etc). In fact even for ambient noise in land boreholes at the same frequency the ratio of geophone to hydrophone response varies by over 12dB between holes. There is no simple relationship between the observed pressure and particle velocity.

On the seafloor the ratio of geophone to hydrophone response is fairly constant over the band for ambient noise (-72 to -82dB) and surface airgun shots (-65 and -72dB). However in Michigan the geophone to hydrophone response ratio for ambient noise is about 20dB greater (-44 to -64dB) and for the land airgun source is 40-50dB greater (between -23 and -37dB).

TABLE 4.1-1: Simultaneous hydrophone and geophone levels in boreholes in field units.

	Geophone dB re: (nm/sec) ² /Hz	Hydrophone dB re: $\mu\text{Pa}^2/\text{Hz}$	Geo/Hydro dB re: (nm/sec) ² / μPa^2
<i>Ambient Noise</i>			
2 Hz			
Marolles	26	84	-58
Michigan	28	72	-44
LFASE	27	99	-72
4 Hz			
Marolles	22	84	-62
Michigan	23	75	-52
LFASE	7	84	-77
8 Hz			
Marolles	12	77	-65
Michigan	13	73	-60
LFASE	0	81	-81
16 Hz			
Marolles	8	76	-68
Michigan	9	73	-64
LFASE	1	80	-79
32 Hz			
Marolles	-3	75	-78
Michigan	5	69	-64
LFASE	2	84	-82
<i>Controlled Source</i>			
2 Hz			
Michigan	46	76	-30
LFASE	30	102	-72
4 Hz			
Michigan	54	77	-23
LFASE	21	97	-76
8 Hz			
Michigan	56	83	-27
LFASE	25	104	-80
16 Hz			
Michigan	52	83	-31
LFASE	31	96	-65
32 Hz			
Michigan	47	84	-37
LFASE	25	107	-82

In designing systems to acquire both hydrophone and geophone data in boreholes it is necessary to consider the environment and objectives. Optimum gain strategies will differ for ambient noise studies, marine reflection/refraction studies or land source studies.

4.2 INSTRUMENT AND FIELD NOISE

One application of SEABASS is to measure the ambient seismic noise in the seafloor in the frequency band 2 to 50Hz. Two questions immediately arise. Is the geophone used in SEABASS, the Mark Products L-15-LBTWHT, sensitive enough to measure true ambient noise levels? Is the electronic noise of the sensors and amplifiers (that is, of the modified CGG Multilock) less than the signal generated by seafloor ambient noise?

(For this discussion it is useful to review the various stages of the acquisition system (Figure 4.2-1). For the geophone data the overall fixed gain for the digital data is 66dB. To obtain system noise on input to the amplifiers, the geophone is replaced with an equivalent resistor. The observed noise level in the digital data stream is then converted into an 'equivalent system noise level on input to the amplifiers' in electronic units (for example, nV). Electronic noise introduced primarily in the amplifier section is included in this value. In this sense, the equivalent system noise level on input to the preamplifiers is a fictional or idealized quantity, but it is useful for comparing systems with different gains and for determining the minimum detectable ground motion. For the case of a hydrophone channel the overall gain is 54dB and the equivalent system noise level is referenced to the input of the hydrophone preamplifier (Figure 4.2-1) which has a gain of -12dB. Since much of the electronic noise is introduced in the 66dB amplifier section the system noise levels on input to the hydrophone preamplifier are about 4 times greater than for the geophone channels. Note that for comparing noise values based on pulse test results (that is, for *in situ* tests where the inputs to both geophone and hydrophone channels are shorted by resistors) the pulse tests are always applied to the input of the 66dB amplifiers.)

Melton (1976) and Riedesel *et al* (1990) give excellent reviews of the issues involved in the sensitivity of inertial seismometers and electronic noise of amplifiers. The sensitivity of the seismometer is limited by the Brownian motion of the air molecules which hit the seismometer mass. The acceleration power spectral density of this Brownian noise is:

$$\frac{A^2}{\text{Hz}} = \frac{8 \pi k T}{m P Q},$$

where k is Boltzmann's constant (1.38×10^{-23} joules/°K), T is absolute temperature (°K, 293° for room temperature and about 274° for the seafloor), m is the seismometer mass (23gm for the L-15-LBTWHT), P is the natural period of the seismometer (4.5Hz for SEABASS), and Q is the damping factor of the seismometer (0.6 for SEABASS). So the Brownian noise level of the SEABASS sensors (two L-15-LBTWHT's in series per channel) at room temperature is $6.6 \times 10 (\text{nm/sec}^2)^2/\text{Hz}$. This is considerably noisier than the Brownian motion for the L22E or the L4C, about 6×10^0 and $1.5 \times 10^{-1} (\text{nm/sec}^2)^2/\text{Hz}$ respectively (Riedesel *et al*, 1990; their

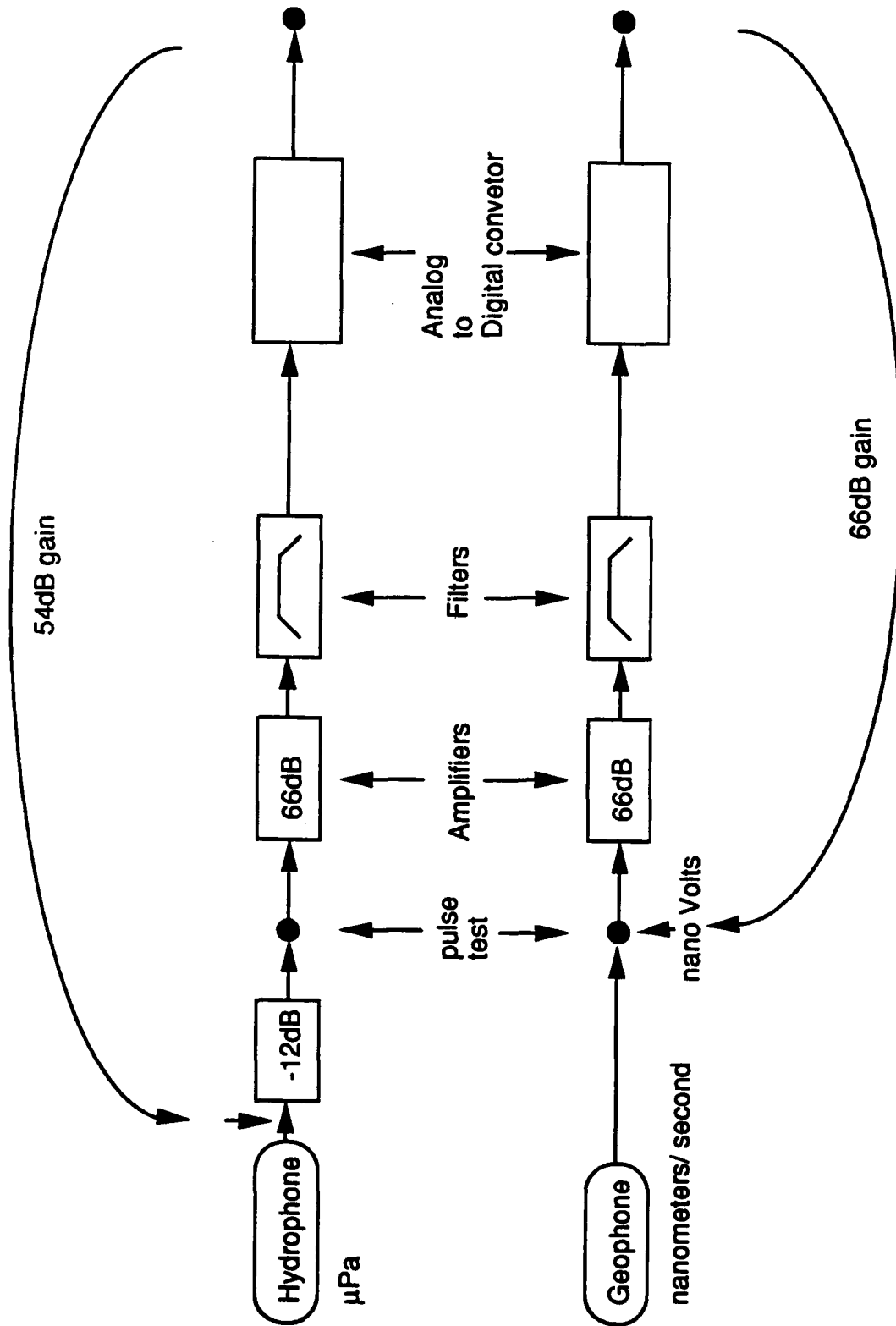


Figure 4.2-1. This figure summarizes the various steps in the acquisition procedure for hydrophone and geophone data. The overall gains for the two acquisition streams are 54dB and 66dB respectively. The 'effective noise on input' for the geophone channels is computed at the input to the 66dB amplifiers and for the hydrophone it is computed at the input to the -12dB preamplifier. For both systems pulse tests, including the *in situ* system noise test, are applied at the input to the 66dB amplifiers.

Figure 12), but the L-15-LBTWHT is a smaller geophone better suited to a portable borehole system. (At seafloor temperature the Brownian noise of the L-15-LBTWHT's is $6.2 \times 10 (\text{nm/sec}^2)^2/\text{Hz}$.)

The Brownian noise level alone is never observed in inertial seismometers since the resistance of the seismometer coil and damping resistor contribute 'Johnson noise' and the operational amplifier in the first gain stage contributes voltage and current noise ($1/f$ noise) as well as additional Johnson noise from the resistive circuit elements. The contribution of these noise sources to the total electronic noise in SEABASS is shown in Figure 4.2-2 in units of nV^2/Hz on input to the amplifiers.

The first stage operational amplifier for the SEABASS geophone channels is a Precision Monolithics OP-27. It is implemented as a non-inverting amplifier with a gain of 38dB (Géomécanique and Compagnie Générale de Géophysique, 1988b). The source resistance for this design is the effective resistance of the two damped geophones ($0.963\text{K}\Omega$, the equivalent of the two coil and two damping resistors in parallel with a $30\text{K}\Omega$ positive input bias resistor) which is close to the ideal noise resistance of the operational amplifier ($1.06\text{K}\Omega$ at 0.1 Hz and $2.06\text{K}\Omega$ at 10 Hz). The total theoretical electronic noise level at 10Hz is $3.41 \times 10 \text{ nV}^2/\text{Hz}$. For comparison the quietest electronic noise at 10 Hz for the configurations discussed by Riedesel *et al* (1990; Figure 4) corresponds to $2.8 \times 10 \text{ nV}^2/\text{Hz}$ on input ($3.0 \times 10^{-12} \text{ V}^2/\text{Hz}$ on output adjusted for a amplifier gain of 30dB).

A bench test was carried out to check the electronic noise level of the amplifier (Géomécanique, 1988d). The input to the geophone channels was shorted with a $1\text{K}\Omega$ resistor (the effective resistance of the two seismometer coils and damping resistances) and spectra of the output noise were observed on a spectrum analyser. At room temperature (20°C), the average of 32 spectra gave a flat curve between 2 and 40Hz at a level of $3.72 \times 10 \text{ nV}^2/\text{Hz}$ at the amplifier input. This level is comparable to the theoretically predicted noise (Figure 4.2-2). (At 0°C the noise level was $2.81 \times 10 \text{ nV}^2/\text{Hz}$.) The electronic noise of the modified CGG Multilock used in SEABASS is considered quite acceptable in relation to the theoretically achievable limits and in relation to other seismometer/amplifier configurations used for seafloor noise studies.

To confirm that the electronic noise specifications were being met on the seafloor under *in situ* conditions we acquired 'pulse test' records (see Section 2.3) during the LFASE experiment (see Section 6.8). In this test records were acquired while the geophones were replaced with 470Ω resistors in the DTU. The *in situ* pulse test spectrum compared favourably with the theoretical total electronic noise curve (Figure 4.2-3).

Figure 4.2-4 compares the ambient noise spectrum for a quiet interval on LFASE with the combined effect of Brownian noise and electronic noise levels of SEABASS. The observed subseafloor noise levels from LFASE are clearly well above the total theoretical noise level from 2.0 to 50Hz . SEABASS is faithfully acquiring true ambient noise data from the seafloor.

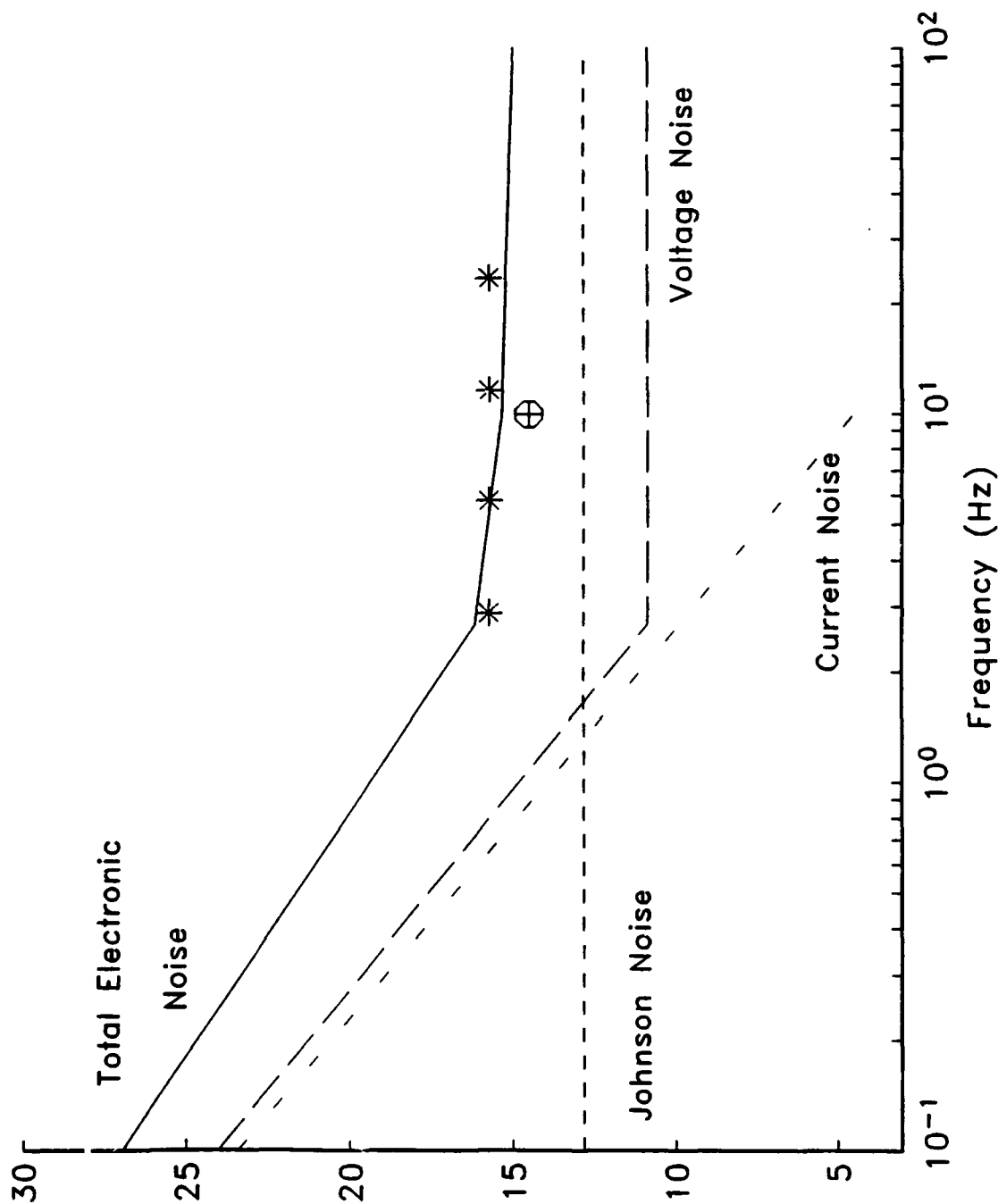


Figure 4.2-2. The electrical system noise of the SEABASS amplifier consists of voltage noise, current noise and Johnson noise. The total electronic noise agrees favourably with the electronic noise levels (stars) measured in the laboratory with the geophones replaced by $1\text{K}\Omega$ resistors. The quietest electronic noise at 10 Hz for the configurations discussed by Riedesel *et al* (1990; Figure 4) is shown as a cross inside an octagon. The observed noise level of the SEABASS amplifier is within 2dB of the theoretically achievable limits and other 'state-of-the-art' systems. (The noise curves in this figure are computed for a $1\text{K}\Omega$ source resistance at 293°K . The results are presented as effective electronic noise levels at the input to the amplifier.)

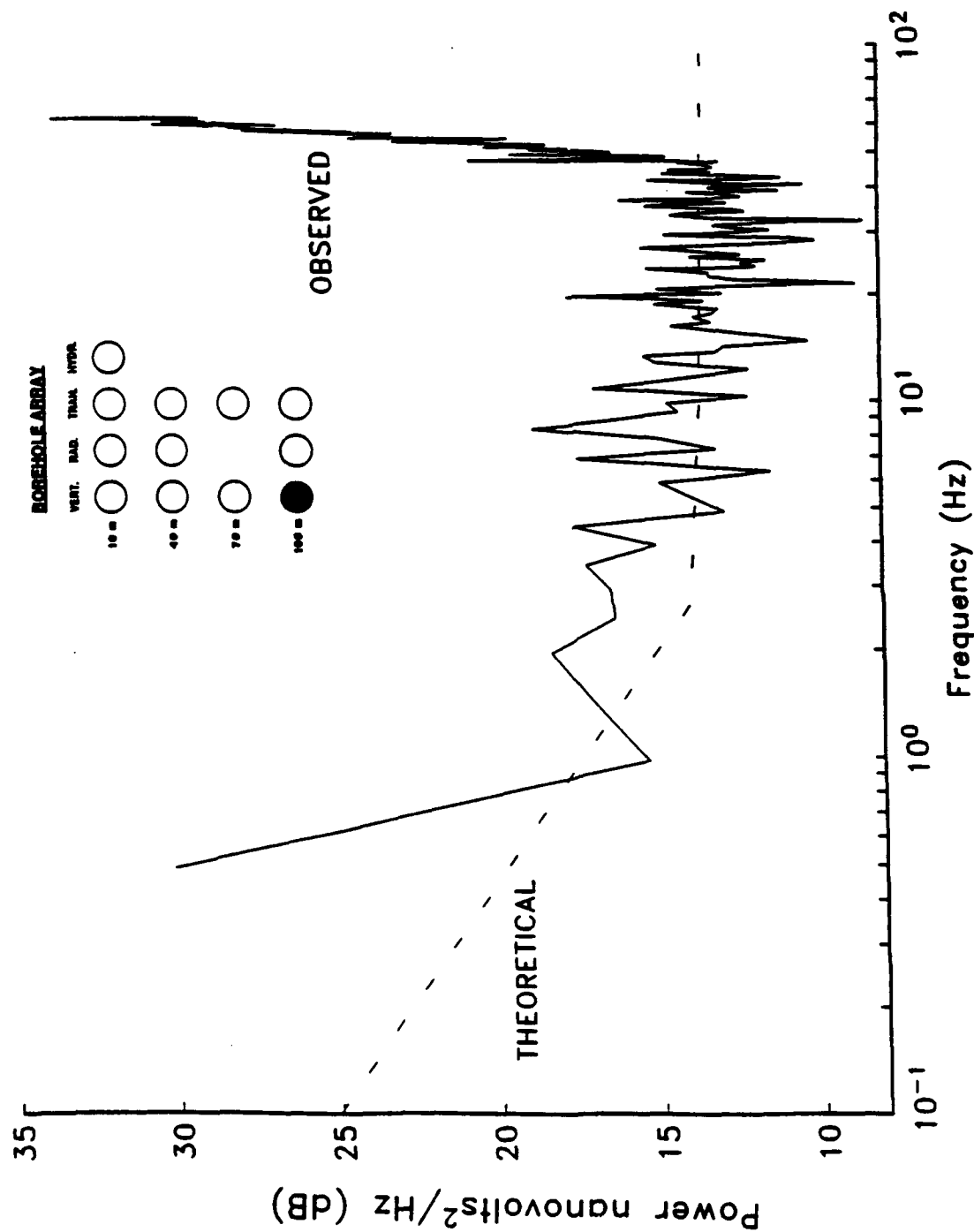


Figure 4.2-3. The total theoretical electronic noise agrees well (within 6dB) with the measured electronic noise spectrum from the seafloor in the band 2-50Hz. These data were acquired during an *in situ* pulse test with the geophones replaced by 470Ω resistors. The spectrum, which has been corrected for the system transfer function, rises sharply above 50Hz because of aliased noise. (The electronic noise spectrum was computed over 1500 points (12sec) using a 256 point averaging window. The theoretical noise curve is computed for a 470Ω source resistance at 274°K. The results are presented as effective electronic noise levels at the input to the amplifier.)

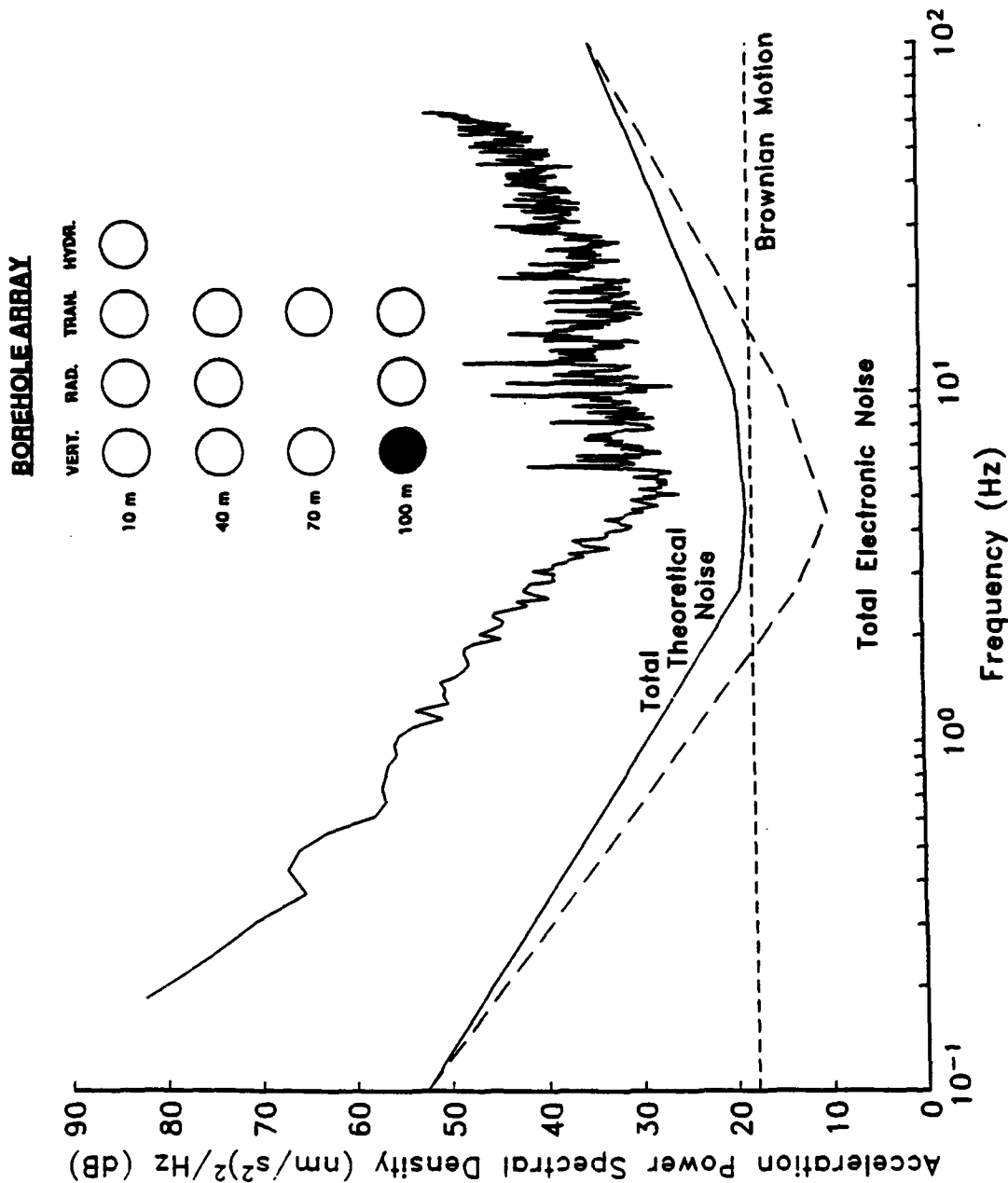


Figure 4.2-4. The total system noise of SEABASS consists of Brownian noise in the geophones and electrical system noise from the amplifiers. Brownian noise is the major contributor to the total theoretical noise between 2.0 and 20Hz. The theoretical noise is at least 10dB less than the observed ambient noise in the seafloor for a quiet interval. This demonstrates that the LFASE results are not being contaminated by system noise. (The spectrum shown corresponds to the vertical channel of the bottom node. It is computed over 44,997 points (6min) using a 2048 point averaging window. The total electronic noise in this figure is computed for a 1,000Ω effective geophone resistance at 274°K. The results are presented as effective ground acceleration at the geophone.)

For most of the nominal passband of SEABASS (2-50Hz) the total system noise is dominated by the Brownian noise (Figure 4.2-4). The Brownian noise is determined by the relatively small mass of the geophones and the low Q required to eliminate ringing. To lower the system noise level further requires going to either larger geophones or to more sophisticated sensor electronics (such as applying feedback to a high Q sensor or using a displacement sensor). If we assume that a portable, rugged and inexpensive multisonde borehole system requires a velocity transducer design with small, passive geophones then the amplifier in SEABASS is quite acceptable.

Figure 4.2-5 compares the SEABASS theoretical noise level (Brownian geophone noise and electronic system noise) with the quietest land measurements acquired at Queen Creek (Fix, 1972) and La Jitas (Herrin, 1982; Li *et al*, 1984). SEABASS would not be able to detect true ambient noise levels at these sites. However, typical quiet land stations are about 20dB noisier than these levels (Figure 10.11 in Aki and Richards, 1980). SEABASS could be used to measure ambient noise at most land stations. Also shown for comparison is the quiet LFASE noise spectrum (from Figure 4.2-4) which is 20dB or more higher than the quietest land stations.

For general interest, Figure 4.2-6 compares vertical velocity spectra from the Paris basin (1540m depth at Marolles), the Michigan basin (50m depth), and the seafloor as acquired on LFASE (10m depth). The seafloor noise is quietest between 2.0 and 20Hz by as much as 20dB but it is remarkable how similar the three spectra are below 2.0Hz and above 20Hz. The ambient noise sources and propagation mechanisms must differ considerably between these sites.

Figure 4.2-7 shows the electronic noise level on the hydrophone channel acquired in the laboratory and a quiet field noise record from LFASE. For the electronic noise level of the hydrophone we shorted the input to the hydrophone preamplifier with a 0.015μ farad capacitor. The electronic noise for the hydrophone channel is higher than for the geophone channels because of the -12dB preamplifier used with the hydrophone element. We did not compute a theoretical noise level for the hydrophone and its preamplifier and we did not compute the effective 'Brownian' noise of the hydrophone element. However, the field noise level is at least 20dB above the electronic noise level throughout the band. The extra sensitivity of the hydrophone to ambient noise and controlled sources compensates for the increased electrical noise (also see Section 4.3).

Figure 4.2-8 compares ambient noise levels on a borehole hydrophone from the Paris basin, the Michigan basin, and the seafloor for the same intervals as the geophone noise levels in Figure 4.2-6. The ambient pressure levels have a different behaviour to the ambient geophone levels. The ambient pressure signal in the borehole is not simply related to the vertical ambient ground motion at the well. The similarity in ambient pressure levels at the three sites between 6 and 30Hz is quite striking.

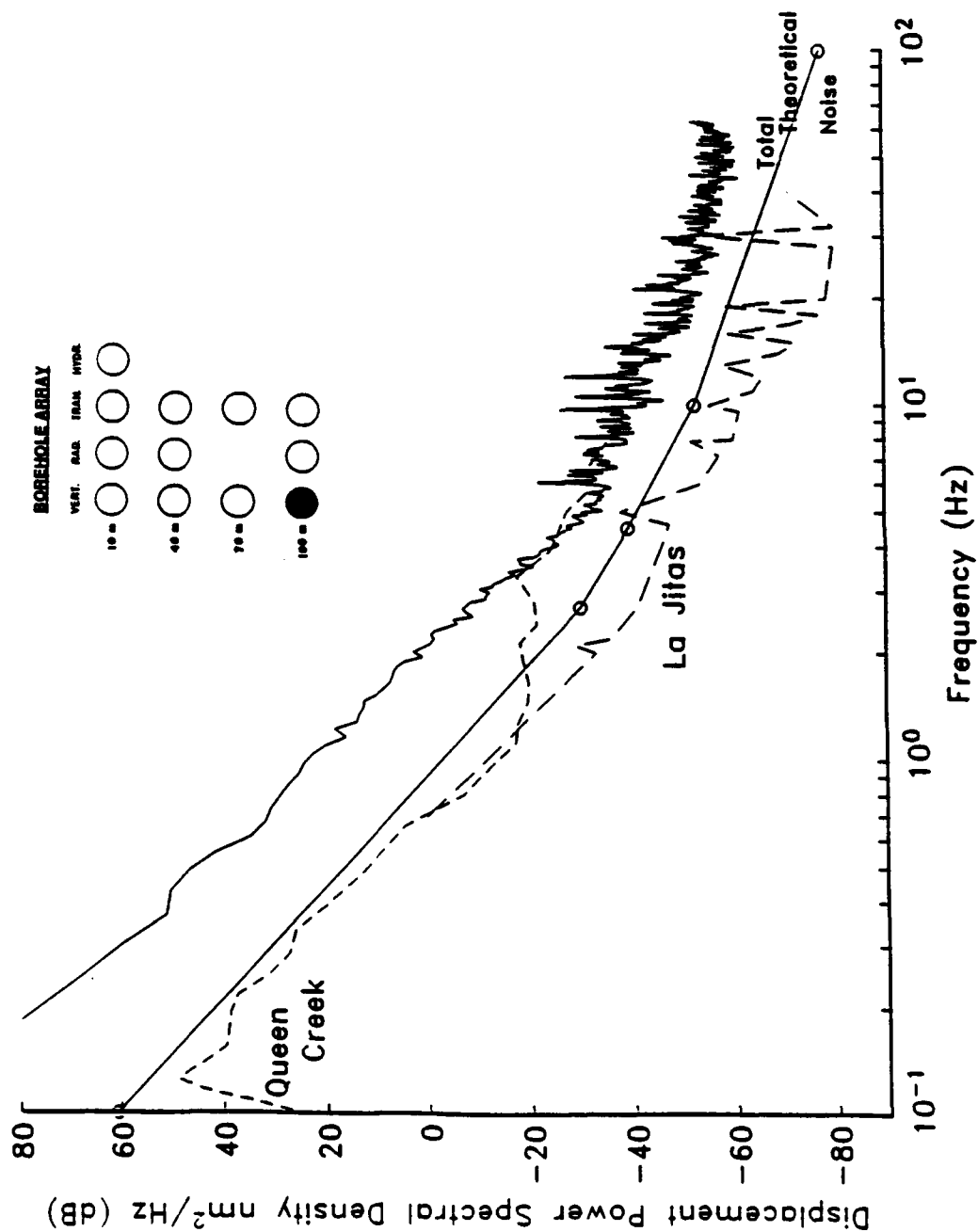


Figure 4.2-5. The theoretical system noise of SEABASS is comparable to the ambient noise observed at the quietest land stations (Fix, 1972; Li *et al.*, 1984; Herrin, 1982) in the band 0.1 Hz to 40 Hz. SEABASS, as currently configured, would not be an appropriate system to measure ambient noise under these conditions. However these 'quietest' land stations have levels about 20 dB below typical 'quiet' stations and SEABASS would be a good, rugged, reliable sensor for most sites. (The LFASE spectrum shown is the same as in Figure 4.2-4. The results are presented as ground displacement at the geophone.)

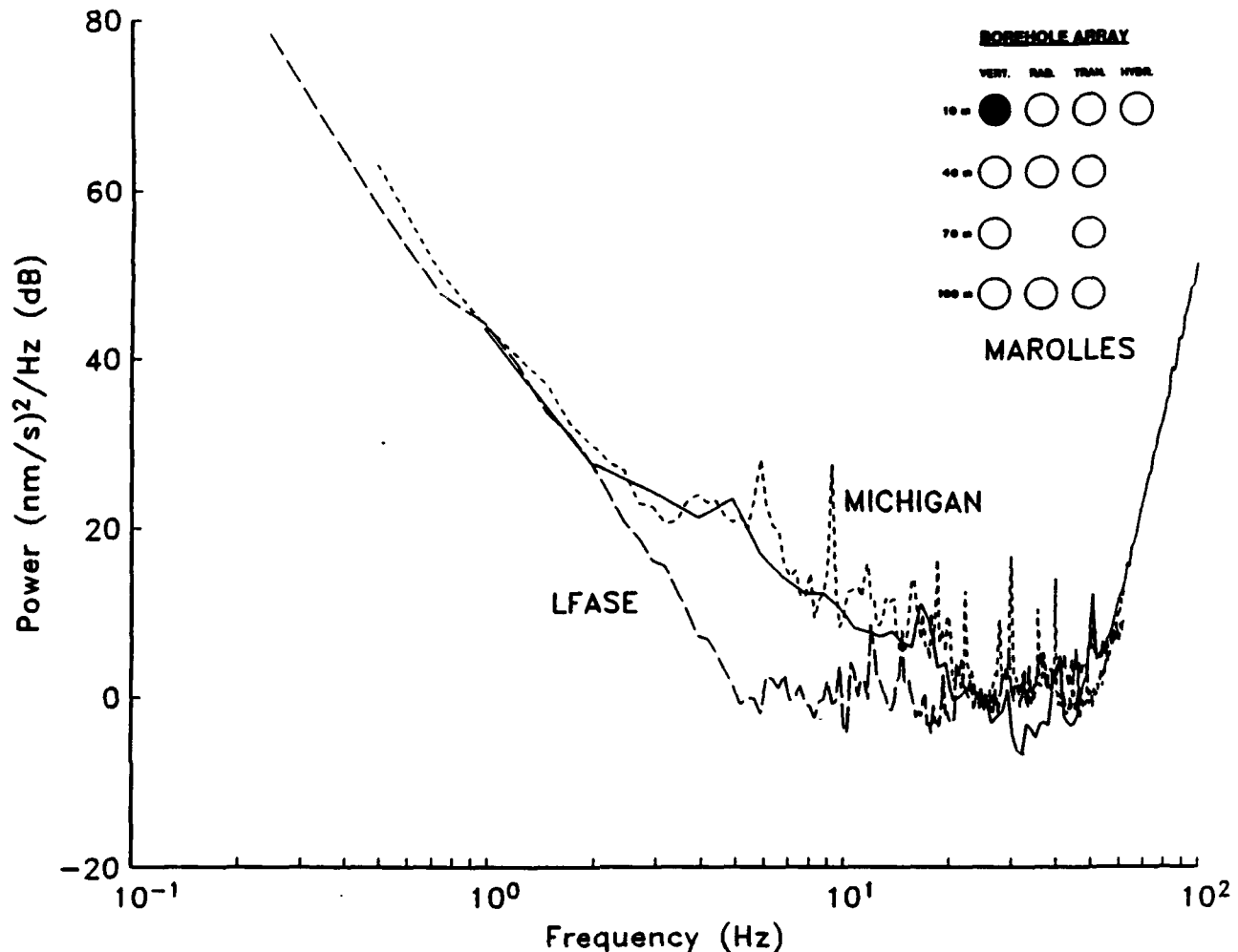


Figure 4.2-6. The ambient vertical component noise is compared between Marolles (at 1540m depth during a fall day at a noisy land site in the Paris basin, solid line), Michigan (at 50m depth during a quiet winter's night in a rural setting, short dashed line), and LFASE (10m below the deep sea floor in the Blake-Bahama Basin, long dashed line). In the microseism band below 2.0Hz the levels are remarkably similar. Between 3.0 and 20Hz LFASE is up to 20dB quieter than the land stations. The LFASE and Michigan levels are comparable above 20Hz. There is a narrow band between 30 and 40Hz for which the Marolles data are quieter than Michigan and the seafloor. The similarity of these noise levels is remarkable given the dramatic differences in environments. The ambient noise sources and propagation mechanisms must differ considerably between these sites. (For the Marolles, Michigan and LFASE spectra the window lengths are 8,000 points (16sec), 20,000 points (2.67min) and 44,997 points (6min) respectively. The averaging window for all three data sets is 512 points. The results are presented as ground velocity at the geophone.)

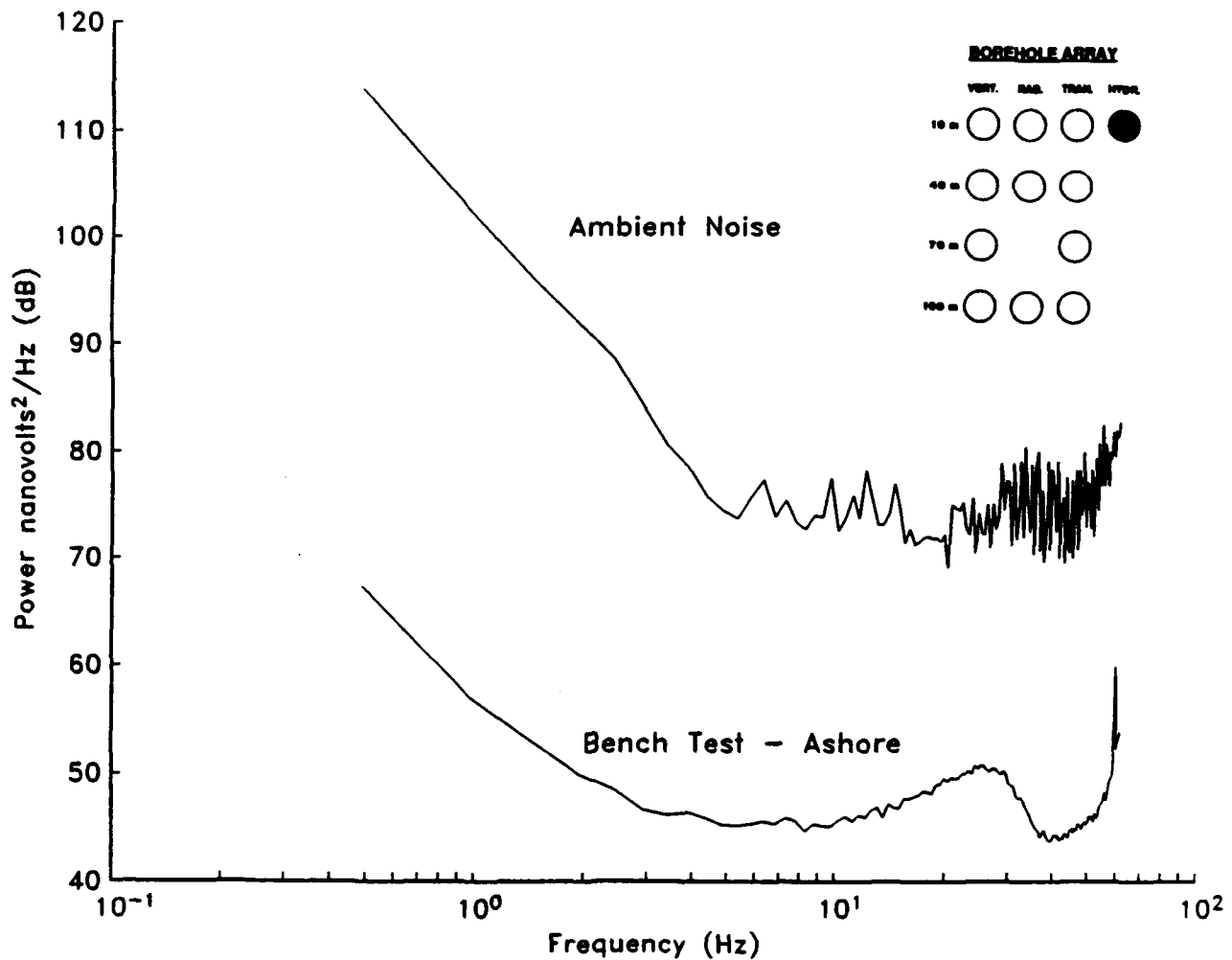


Figure 4.2-7. The measured electronic noise spectrum on the hydrophone channel (with the hydrophone replaced by a capacitor) is compared with the observed hydrophone level from a quiet period on LFASE. The observed level is at least 20dB greater throughout the band, confirming that the LFASE hydrophone results are not being contaminated by system noise. (For the LFASE and electronic noise spectra the window lengths are 44,997 points (6min) and 44,000 points (5.87min), respectively. The averaging window for both spectra is 256 points. The results are presented as effective electronic noise levels at the input to the hydrophone preamplifier.)

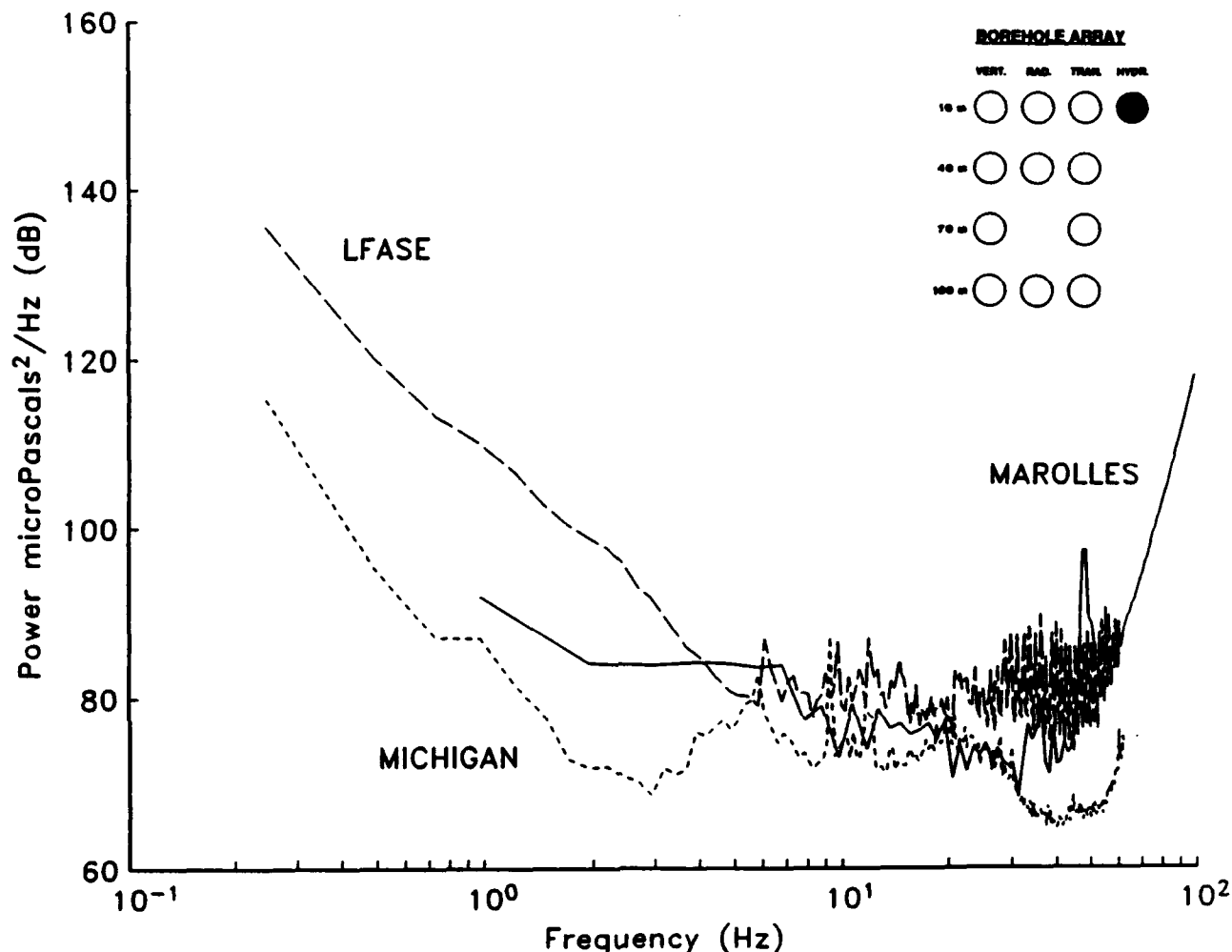


Figure 4.2-8. The ambient pressure noise is compared between Marolles (solid line), Michigan (short dashed line) and LFASE (long dashed line). In contrast to the vertical motion (Figure 4.2-6), during the same time intervals at the same locations, the pressure field is quite different at the three sites below 5.0Hz. Levels between 5.0 and 30Hz are comparable at all three sites. Below 5.0Hz and above 30Hz the quietest ambient pressure noise was observed in Michigan. The physics of ambient noise for the velocity field and the pressure field must be dramatically different. Marolles, which was a day time measurement in the Paris Basin and was subject to considerable cultural noise, has comparable levels to the deep sea floor. It is surprising that the Michigan levels, acquired in a rural land area during a quiet winter's night, are as much as 10dB quieter than the deep sea levels at some frequencies. (The spectra were computed using the same values as Figure 4.2-6. The results are presented as pressure values at the hydrophone which was colocated (within 1.5m) with the geophone in Figure 4.2-6.)

4.3 HYDROPHONE GAIN STRATEGY

One objective of SEABASS is to measure the pressure in the borehole, corresponding to both signals and ambient noise, for comparison with the ground motion observations. Hydrophones and geophones are very different sensors responding to different physical phenomena with different sensitivities (see Section 4.1). Care should be taken in combining both pressure and ground motion sensors in the same acquisition system.

For both hydrophones and geophones the first requirement is that the electrical signals corresponding to observed ambient noise be greater than the electrical system noise (see Section 4.2). The second requirement is that the electrical signals in the acquisition system, corresponding to system noise, ambient seismo-acoustic noise and controlled source signals be of comparable amplitude for geophones and hydrophones. This minimizes the effects of crosstalk between channels and gives comparable dynamic range for both sensors.

For ambient noise and controlled sources for which we have data from SEABASS, the ratio of geophone signals to hydrophone signals at input to the digitizer in electronic units varies from -27dB to 32dB (see Table 4.3-1) depending on frequency, location, etc. Ideally this value should be 0dB. This confirms, for this range of sites, depths, and frequencies, that the SEABASS gain strategy (54dB for hydrophones and 66dB for geophones) is about correct for the range of tests carried out.

For the particular application of measuring ambient noise and signals in boreholes on the seafloor (with hydrophone to geophone signal ratios of -10dB to -27dB) it would have been better, in retrospect, if the hydrophone were desensitized a further 20dB. The higher sensitivity of the hydrophone simply reflects the fact that the hydrophone as configured on SEABASS gave a much higher voltage output than the geophones for the same *in situ* conditions. This does not mean that hydrophones have a better signal-to-noise ratio than geophones since the increased sensitivity applies to both ambient geo-acoustic noise and controlled sources. The hydrophone gain strategy on SEABASS ensures good ambient noise observations. However the dynamic range of the hydrophone channel is about 20dB less than for the geophone channels and the hydrophone signals frequently clip at short ranges (Bolmer *et al*, 1991).

Given the program constraints for LFASE, we were obliged to stay with the fixed Multilock design where the geophone amplification was carried out in the DTU, separate from the satellites. The hydrophone preamplifier, mounted in the top satellite, initially had a gain of 34dB (because this was the gain used for previous hydrophone applications at WHOI). Another 20dB of gain was applied in the DTU amplifiers (to give an overall gain of 54dB) but the crosstalk level on the cable between the top sonde and the DTU was unacceptable. As a compromise between crosstalk in the cable, dynamic range of the digitizer, and electronic system noise on the hydrophone channel we used a -12dB gain in the hydrophone preamplifier and 66dB gain in the DTU amplifiers. If a system were being designed from scratch the geophone amplifiers should be placed at the geophones (in the sondes) and the amplifier gains would be selected so that geophone and hydrophone signals on the cable and at input to the

TABLE 4.3-1 Simultaneous hydrophone and geophone levels in boreholes in electronic units on input to the DTU ampfilt section in the SEABASS system. (For equivalent voltage output from the hydrophone transducer add 12dB to the hydrophone values.)

	Geophone dB re: nV ² /Hz	Hydrophone dB re: nV ² /Hz	Geo/Hydro dB re: 1
Ambient Noise			
2 Hz			
Marolles	63	65	-2
Michigan	65	53	11
LFASE	63	80	-17
4 Hz			
Marolles	59	65	-6
Michigan	60	56	3
LFASE	44	65	-22
8 Hz			
Marolles	48	58	-10
Michigan	49	54	-5
LFASE	36	62	-26
16 Hz			
Marolles	44	57	-13
Michigan	45	54	-9
LFASE	37	61	-24
32 Hz			
Marolles	33	56	-23
Michigan	42	50	-8
LFASE	38	65	-27
Controlled Source			
2 Hz			
Michigan	82	57	25
LFASE	66	83	-17
4 Hz			
Michigan	90	58	32
LFASE	57	78	-21
8 Hz			
Michigan	93	64	28
LFASE	61	85	-24
16 Hz			
Michigan	88	64	24
LFASE	67	77	-10
32 Hz			
Michigan	84	65	18
LFASE	61	88	-26

digitizer would have comparable amplitude. (It would be better still to digitize and multiplex in each sonde.)

4.4 TRANSFER FUNCTIONS

The transfer function, from ground motion or borehole pressure to electrical signal on input to the digitizer, is comprised of four parts: the transducer, the DTU amplifier, the high cut filter and the low cut filter. For each seismometer channel there are two geophones in series with a combined response given by:

$$G(s) = \frac{s^2 T_9^2 \times 6.54 \times 10}{1 + 2 s \zeta_3 T_9 + s^2 T_9^2} \text{ nV/nm/sec,}$$

The values of T_i and ζ_i are summarized in Table 4.4-1. The Laplace transform variable, s , corresponds to $i\omega$, where ω is angular frequency and i is the square root of -1 .

The borehole hydrophone consists of the transducer and a built-in hydrophone preamplifier separate from the amplifiers in the Data Telemetry Unit (see Section 4.3). We present here the transfer function for the -12dB hydrophone preamplifier which uses the same DTU amplifier as the seismometer channels. The combined response for the hydrophone and its preamplifier is:

$$H(s) = \frac{sT_{11}}{sT_{11} + 1} \times \frac{sT_{12}}{sT_{12} + 1} \times 1.12 \times 10^{-1} \text{ nV/}\mu\text{Pa.}$$

The twelve channels in the Data Telemetry Unit each have an amplifier response given by:

$$A(s) = \frac{1}{sT_1 + 1} \times \frac{1}{sT_2 + 1} \times 2.00 \times 10^3$$

The high cut filter consists of two 5-pole Butterworth filters with a combined response, for all twelve channels, of:

$$B(s) = \left\{ \frac{1}{sT_3 + 1} \times \frac{1}{1 + 2\zeta_1 sT_3 + s^2 T_3^2} \times \frac{1}{1 + 2\zeta_2 sT_3 + s^2 T_3^2} \right\}^2$$

TABLE 4.4-1: TRANSFER FUNCTION PARAMETERS

The parameters are:

$$T_1 = 1.8 \times 10^{**} (-4), \quad (f_{hi-cut} = 884 \text{ Hz})$$

$$T_2 = 2.4 \times 10^{**} (-4) \quad (f_{hi-cut} = 663 \text{ Hz})$$

$$T_3 = 3.658 \times 10^{**} (-3) \quad (f_{hi-cut} = 43.5 \text{ Hz})$$

$$T_8 = 7.234 \times 10^{**} (-2) \quad (f_{low-cut} = 2.20 \text{ Hz})$$

$$T_9 = 3.54 \times 10^{**} (-2) \quad (f_{low-cut} = 4.50 \text{ Hz})$$

$$T_{11} = 1.01 \times 10^{**} (-1) \quad (f_{low-cut} = 1.575 \text{ Hz})$$

$$T_{12} = 3.35 \times 10^{**} (-1) \quad (f_{low-cut} = 0.475 \text{ Hz})$$

$$\zeta_1 = 0.304$$

$$\zeta_2 = 0.810$$

$$\zeta_3 = 0.600$$

(The Nyquist frequency of the digitizer is 62.5 Hz.)

There is one low cut filter in the amplifier/filter section and one in the digitizer. They are identical and their combined response is:

$$C(s) = \left(\frac{sT_8}{sT_8 + 1} \right)^2$$

So the transfer function for the seismometer channels is the product $G(s)A(s)B(s)C(s)$ and the transfer function for the hydrophone channels is $H(s)A(s)B(s)C(s)$. The amplitude and phase of these functions are plotted in Figures 4.4-1 and 4.4-2, respectively. Actual system gains as measured on the individual 'as built' amplifier/filters are reported in Géomécanique (1988a) and are within 1dB of nominal values.

The passband for the geophone channels (as defined as the band between the 3dB down points) is 4.7Hz to 40Hz. The low end is determined by the response of the geophone and the high end is determined by the anti-aliasing filters. The passband for the hydrophone channel is 3.9Hz to 40Hz. The low end is determined by the low cut filters in the DTU and the high end is determined by the anti-aliasing filters which are the same as for the geophone channels. Both passbands are smaller than the nominal bandwidth that was prescribed for SEABASS, 2.0 to 50 Hz.

Some compromises were made in the passband to facilitate the instrument design (in order to meet a tight schedule for the LFASE sea test) and to meet reasonable data storage and power consumption parameters in the seafloor system. In order to meet the schedule for the experiment it was necessary to use an existing borehole array. At the time that the project was conceived (summer of 1987) the CGG Multilock was the only available digital borehole array that had been field tested. The original Multilock, designed for a passband of 10 to 125Hz, digitized the twelve data channels at 500samples/sec. By simply subsampling by a factor of four (and changing the filters) we could approximate the required LFASE passband of 2-50Hz. At a sampling rate of 125samples/sec we could acquire about 41 hours of data which could be stored on 600Mbytes. This could be accomplished using three 200 Mbyte optical disk recorders, which also existed and had been field tested by the summer of 1987, and the whole seafloor system could be powered by five wet cell batteries. This was a technically feasible scenario which satisfied the scientific objectives in a timely fashion with acceptable risks and costs.

Given a sampling rate of 125 samples/sec, that is determined by program constraints, it is necessary to obtain meaningful seismic data up to 50Hz. For a Nyquist frequency of 62.5Hz, a high cut frequency of 40Hz and a roll-off of 60dB/octave, the aliased noise level at 50Hz is down 38.7dB from its filtered value (Figure 4.4-3). So this configuration is acceptable for energy up to 50Hz if one is willing to accept about 40dB aliased noise rejection. The filtered values at 50Hz are sufficiently high to ensure recovery of meaningful data by applying the inverse of the transfer function. This analysis applies to both the hydrophone and geophone channels.

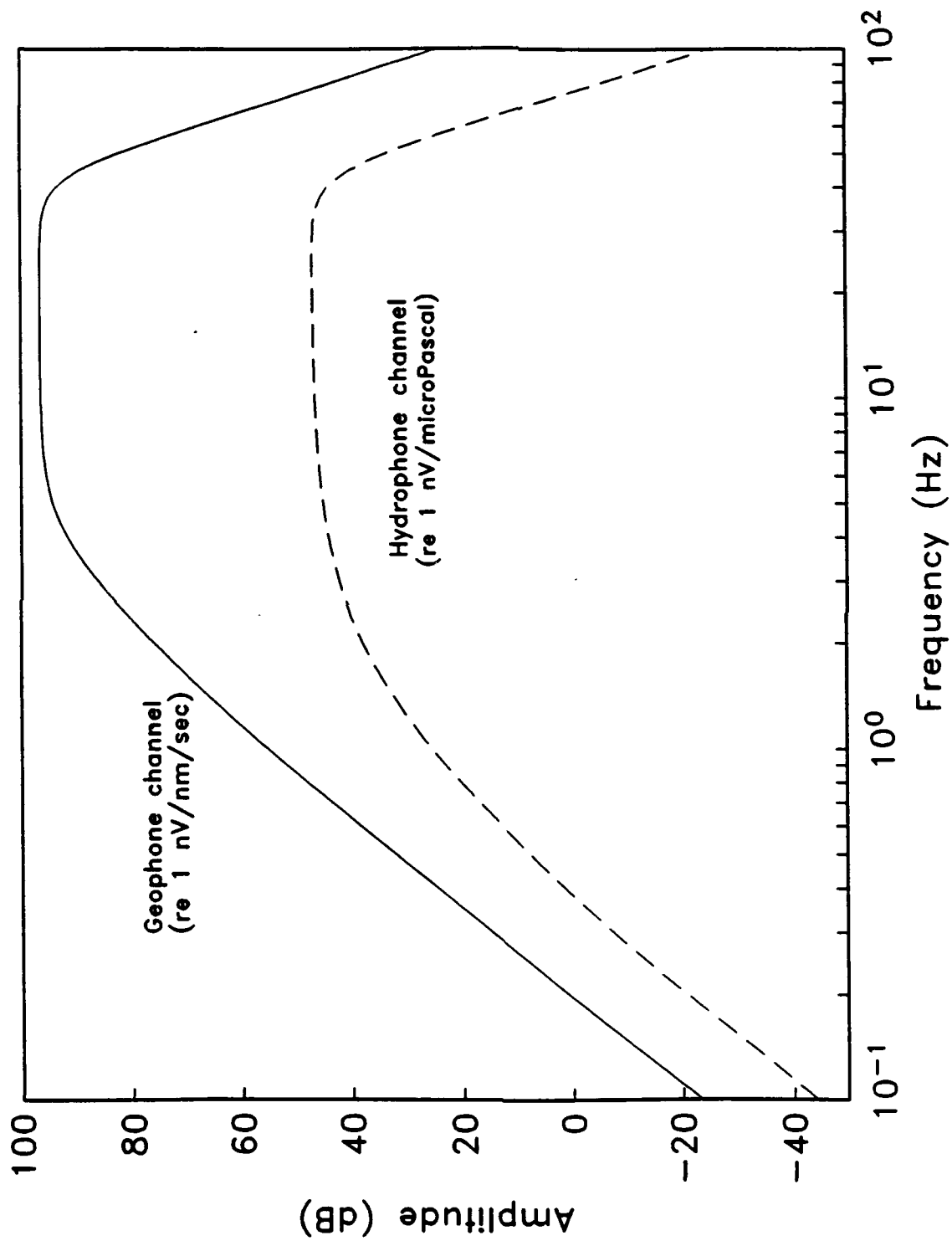


Figure 4.4-1. The amplitude spectra of the SEABASS transfer function for geophone and hydrophone channels are flat within 3dB between 4.7 to 40Hz and 3.9 to 40Hz respectively.

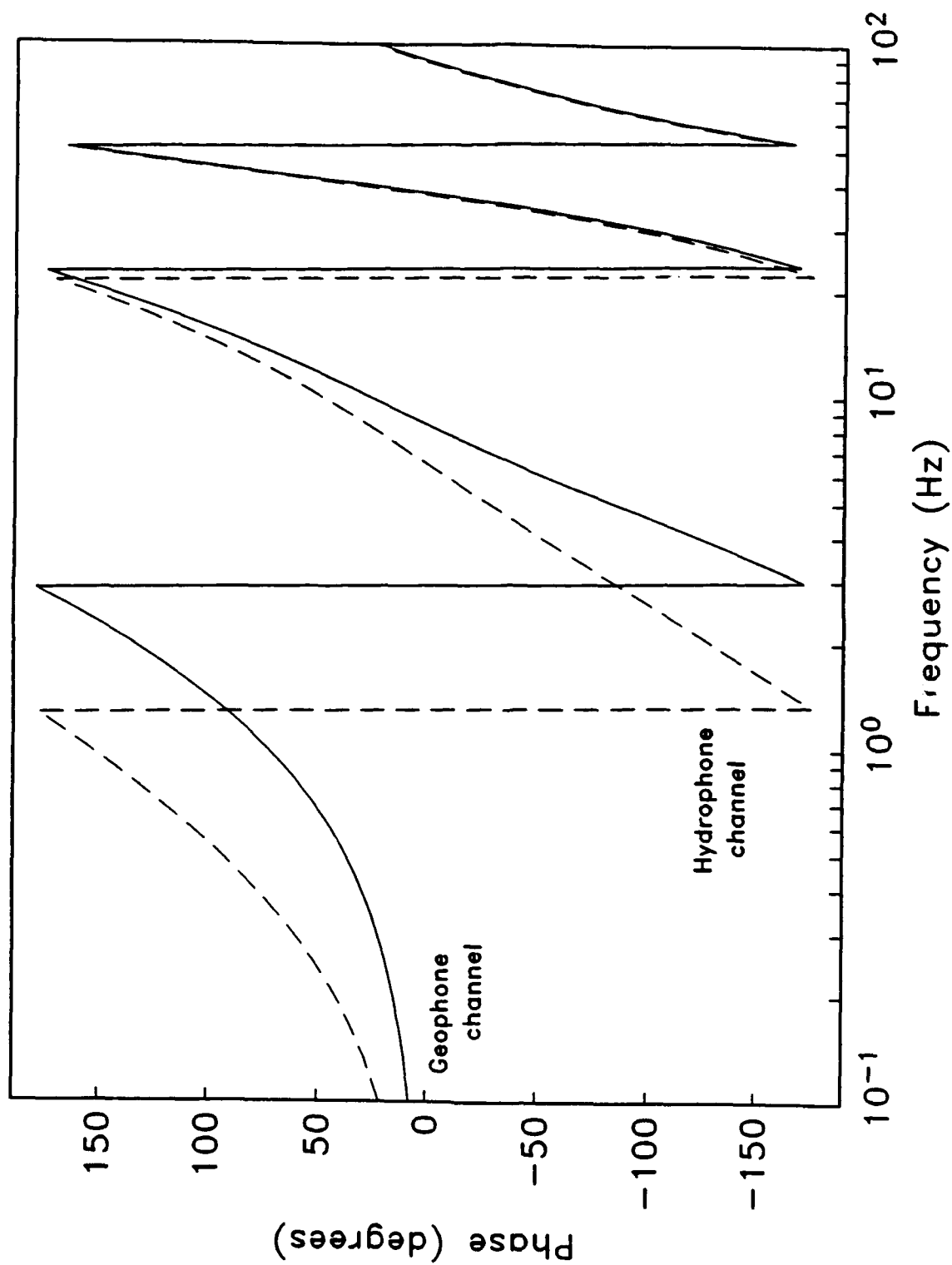


Figure 4.4-2. The phase spectra of the SEABASS transfer function for geophone and hydrophone channels vary considerably in the band 0.1 to 50Hz.

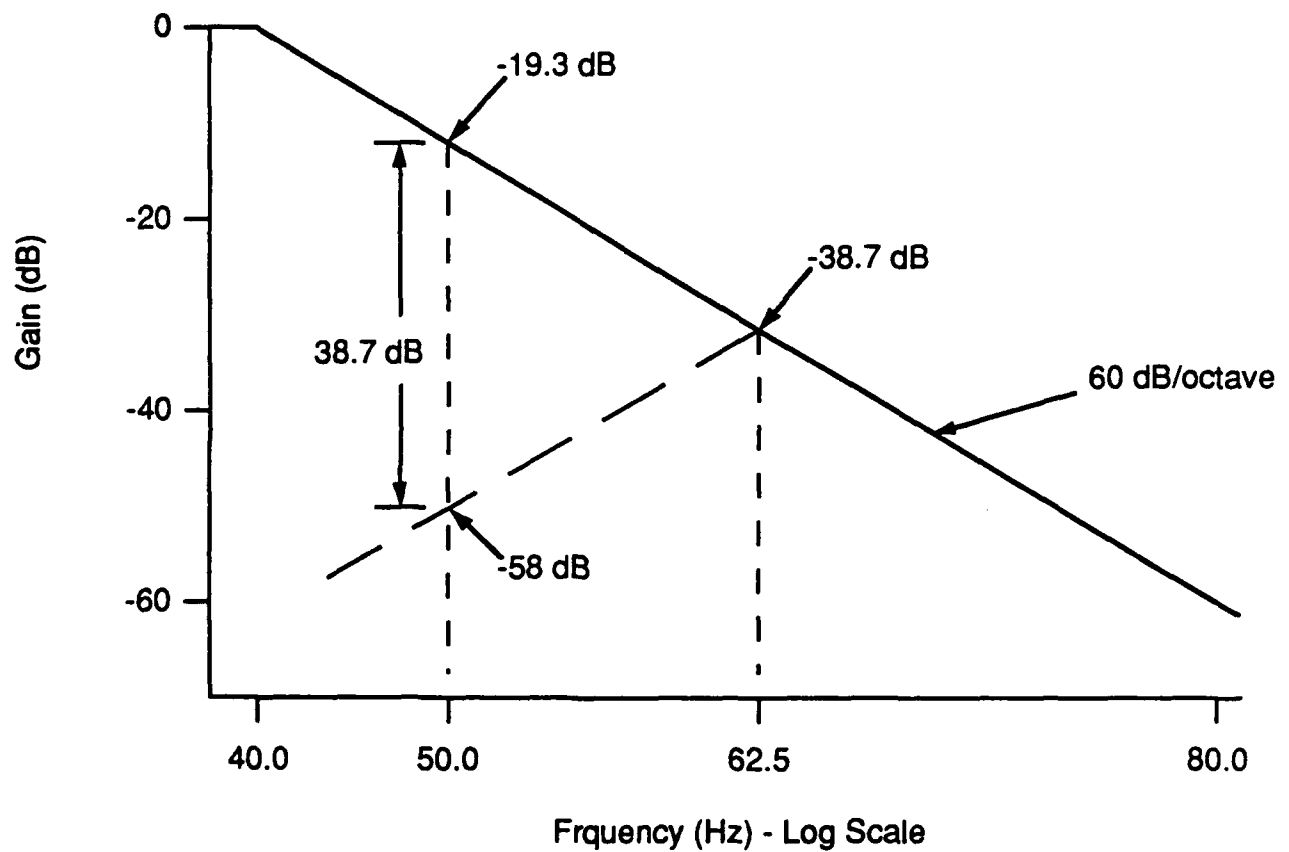


Figure 4.4-3. For the filters and sampling strategy used on SEABASS, the aliased noise at 50Hz is down about 40dB (38.7dB) from the signal.

At the low frequency end the response for the geophone channels is down 20dB at 2.0 Hz and the response for the hydrophone channel is down 10dB. However the ambient noise levels due to microseisms at 2.0 Hz are about 20 dB higher than the levels at 10-40Hz, which are due to shipping and weather (for example see Section 8.1). So the filter is just compensating for earth noise (and perhaps 1/f noise in the amplifiers, see section 4.2) to keep the electrical signals flat.

4.5 THE DIGITIZER AND NUMBER REPRESENTATION

This section summarizes the way the voltage values on input to the digitizer are treated in the SEABASS system. Figure 4.5-1 shows schematically the data flow from ground motion or pressure at the transducers to the 32-bit computer (a Digital Equipment Corporation VAX 8800) used for data reduction and analysis. The transfer functions of the analog section, from the field quantity to the input of the digitizer, are given in Section 4.4.

Data values from the digitizer in the Data Telemetry Unit are represented by 16 bit binary words in A12G4 format as follows:

$G_0 \ G_1 \ G_2 \ G_3 \ S \ M_1 \ M_2 \ M_3 \ M_4 \ M_5 \ M_6 \ M_7 \ M_8 \ M_9 \ M_{10} \ M_{11}$

The voltage on input to the digitizer (and gain ranging amplifiers) is given by (Géomécanique, 1988c):

$$V(\text{mV}) = 2.44 \times M/2^G$$

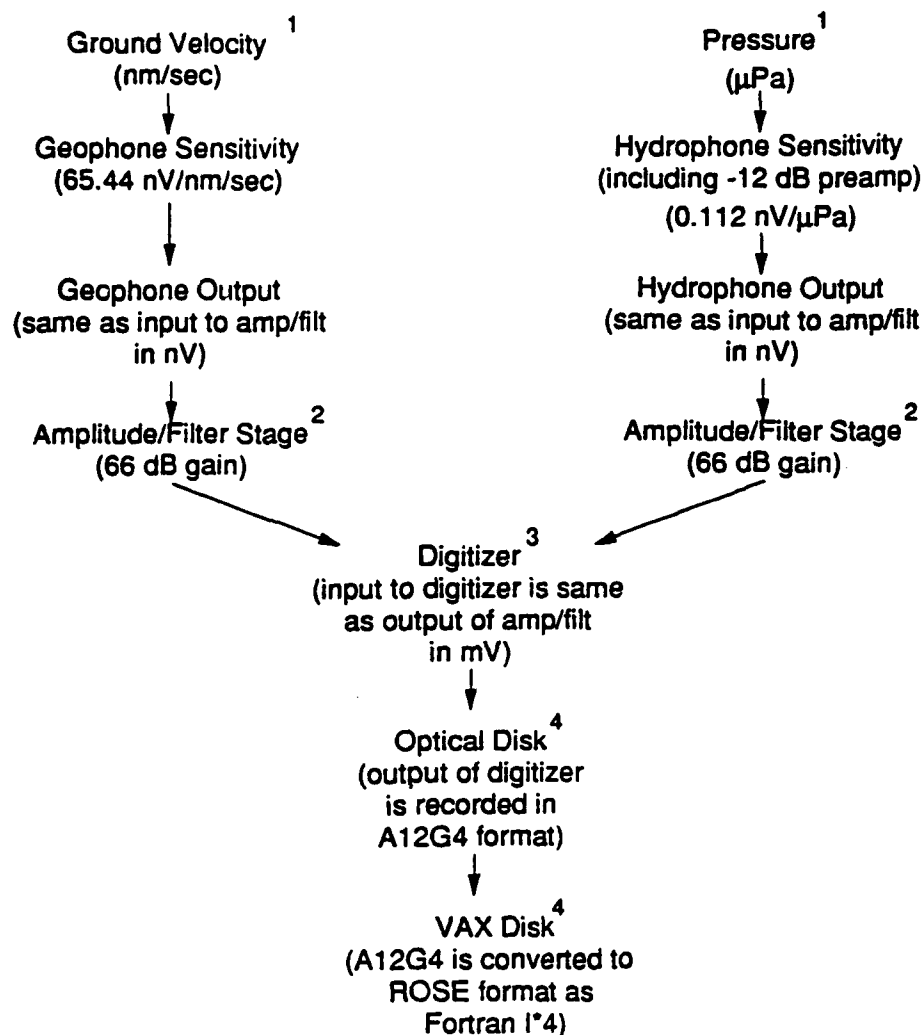
where

$$\begin{aligned} G &= G_0 + 2 G_1 + 4 G_2 + 8 G_3 \\ M &= \sum_i (M_i \times 2^{(i-1)}) \end{aligned}$$

G has a maximum decimal value of 11 corresponding to 11 gain stages of 6dB. S is the sign bit. A12G4 format, also referred to as 'field format' is used by SEABASS for all telemetry and storage on field media. (If accuracy greater than three significant digits is required, a more careful study of the analog to digital converter is necessary.)

It is useful to know the maximum field signal that can be recorded without clipping and the least significant bit (LSB) that can be recorded. (These are summarized in Table 4.5-1) The maximum voltage on input to the digitizer and gain ranging section is $5.00 \times 10^3 \text{ mV}$. The smallest detectable voltage on input to this section is $1.19 \times 10^{-3} \text{ mV}$. The corresponding maximum and minimum ground velocity values are $3.83 \times 10^4 \text{ nm/sec}$ and $0.915 \times 10^{-2} \text{ nm/sec}$, respectively. The corresponding maximum and minimum pressure values are $22.3 \times 10^6 \mu\text{Pa}$ and $5.32 \mu\text{Pa}$ respectively.

SEABASS Data Acquisition Flow Chart



- 1) Actual ground velocities and pressure are converted to voltage signals from the the geophone and hydrophone sensitivities.
- 2) The ouput of the amplifier/filter section is quoted in mV and is obtained from the Geophone and Hydrophone Output by multiplying by $2.00 \times 10.0^{**3}$.
- 3) The digitizer converts the analog levels in mV to an integer value by multiplying by $(2^{**11}) / 2.44141$.
- 4) The numbers on the optical and VAX disks are in different formats: A12G4 on optical disk and Fortran I*4 on VAX. The integer value is obtained by $M \times (2^{**(-G)}) \times (2^{**11})$.

Figure 4.5-1. This figure summarizes the sensitivities and gains at the various levels of the SEABASS acquisition system.

TABLE 4.5-1: SEABASS NUMEROLOGY

<u>Processing Stage</u>	<u>Formula</u>	<u>Largest Positive Number</u>	<u>Smallest Positive Number (LSB)</u>
Field format	A12G4	0000+11111111111	1011+000000000001
Laboratory format	ROSE (INTEGERS)= $M \times 2^{-G} \times 2^{11}$	4,192,256*	1
Input to digitizer	$V(\text{mV}) =$ $\text{ROSE} \times 2.44141 / (2^{11})$	5.00 V	1.19 μV
Input to amp/filters (geophone)	$V_g(\text{mV}) = V(\text{mV}) / 1,995.26^{**}$	2.50 mV	0.597 nV
Input to amp/filters (hydrophone)	$V_n(\text{mV}) = V(\text{mV}) / 501.18^{**}$	9.97 mV	2.38 nV
Ground Velocity	$\text{vel (nm/sec)} =$ $V(\text{mV}) / (1.3057 \times 10^{-1})$	$3.83 \times 10^4 \text{ nm/sec}$	$0.915 \times 10^{-2} \text{ nm/sec}$
Pressure	$\text{p}(\mu\text{Pa}) =$ $V(\text{mV}) / (2.23871 \times 10^{-4})$	$22.3 \times 10^6 \mu\text{Pa}$	5.32 μPa

* The most negative number is -4,194,304 (0000100000000000 in A12G4 where 1 indicates a negative sign).

** In generating this table we have used the nominal values for the system gains in dB and maintained 5 to 6 significant figures. If the transfer function is required to better than three significant figures more care must be taken in the analysis. Actual system gains as measured on the 'as built' amplifier/filters are reported in Géoméchanique (1988a) and are within 1dB of nominal values.

The minimum (theoretical) values from the digitizer are never actually observed because they are much less than the electrical noise of the transducers and analog electronics. The dynamic range of the system can be defined as the ratio of the RMS value of the maximum undistorted signal to the RMS value of the noise (Melton, 1976). (A discussion of electrical system noise levels versus real and estimated values of ambient noise in the field signals is given in Section 4.2.) The RMS value of the maximum undistorted sinusoidal signal, which has a peak amplitude of 5.0V on output, is 1.76×10^{-3} VRMS on input to the amplifier. The RMS value of the system noise referenced to the amplifier input, based on data acquired with the amplifier input shorted with $1,000\Omega$ (the effective resistance of the two damped geophones), is 37.3nVRMS (Géomécanique, 1988b). So the effective dynamic range of the geophone channels in the system is 94dB. Since the theoretical dynamic range of a twelve bit analog-to-digital converter with 66dB of gain ranging is 132dB plus sign, we have 38dB, or about 6bits, in the noise. The effective dynamic range for the hydrophone channel is 73dB. This is based on a measured RMS system noise level of 377.2nVRMS on input to the DTU amplifier (the output of the -12dB hydrophone preamplifier) when the hydrophone is replaced with a 0.015μfarad capacitor.

On the LFASE project the data storage and exchange format was ROSE format (Latraille, 1983; Latraille and Dorman, 1983; Little *et al*, 1990b). In ROSE format each number is represented by a 32 bit integer word. We convert from A12G4 format to ROSE format by simply multiplying by 2^{11} . So a ROSE format number is an integer value:

$$\text{ROSE} = M \times 2^{11} - G.$$

ROSE numbers will range from -4,194,304 to 4,192,256.

4.6 TOOL DIMENSIONS AND USE FROM ODP DRILL SHIPS

The inside diameter of the drill pipe presently being used from the D/V JOIDES Resolution is 104.8mm(4-1/8inch). In borehole seismic experiments carried out from the drill ship and its predecessor the D/V Glomar Challenger (for example, Stephen *et al*, 1980), the borehole seismometers were small enough (92.1mm, 3.62inch) to be lowered through the drill pipe. By using a special 'logging bit' the seismometers could be run out of the drill string into the open hole. The Multilock array used in SEABASS cannot be deployed in this fashion since the outside diameter of a satellite in its slimmest configuration is 112mm(4.39inch). At the present time the Multilock string can only be deployed in deep sea boreholes using the wireline re-entry capability (Spiess *et al*, 1989a; submitted) or submersible assisted re-entry (Legrand *et al*, 1989).

4.7 TEMPERATURE SPECIFICATIONS AND HYDROTHERMAL VENTS

The overall temperature specification of SEABASS is only 20°C, however this applies primarily to the DTU electronics. The cable and mechanical components, which

actually go down the hole are rated to 180°C. Borehole seismic monitoring of seafloor hydrothermal events could be extremely interesting scientifically. SEABASS could be used for these measurements if the maximum temperature in a borehole near the vents did not exceed 180°C and if the BIP and DTU were offset from the well head in cold (less than 20°C) water.

5. DEPLOYMENT CONFIGURATIONS

5.1 VSP CONFIGURATION

In addition to seafloor operation, SEABASS is designed to acquire standard VSP profiles on land or from offshore platforms over a seven conductor logging cable. In this mode the Multilock DTU goes downhole and is unclamped at either 10m or 30m above the top satellite (Table 5.1-1). All satellites and the DTU are connected with 37 conductor cable. The satellites can be separated by either 10m or 30m cable lengths. Standard seven conductor logging cable connects the DTU to the surface. Power is provided from the surface and the long-cable data telemetry mode is selected in the DTU. A blind end cap terminates the bottom of the fourth satellite. Vibroseis sweeps, shots from a land airgun or explosives are used as controlled sources. The array is pulled up the hole and stopped at specific intervals to acquire the data. This Multilock configuration was used for the field acceptance tests in Marolles, France, and for the SEABASS tests in Michigan (see sections 6.5 and 6.6).

The VSP acquisition and recording system used in Michigan is shown in Figure 5.1-1. Shot instants were detected on a base plate accelerometer on the Bolt land airgun and were transmitted to the recording van by wire. (Requests for a shot from the recording van to the shooting truck were made via radio.) The shot instant signal initiated the digitization process (by turning ACQUISYNCHRO on for some operator-selected time window). At the same instant the GOES clock was strobed to latch the time of the first sample into its internal register. The shot instant signal also triggered the oscillographic recorder. Digital data at a 2msec sampling rate were telemetered in HDB3 format from the DTU to the Multilock control unit. The data were converted to 'NRZ plus clock' format in the 'Short cable simulator' and could be subsampled by four in the control computer. Data at either 2msec or 8msec sampling rate were recorded on an Optotech optical disk in the A12G4 format used for seafloor recording. At the end of the time window ACQUISYNCHRO was turned off, stopping the data acquisition. The latched time from the GOES clock was transferred to the computer where it was written in the record trailer on the optical disk.

In this mode the CGG supplied equipment, the Multilock system, operates independently from other SEABASS electronics. This is obviously important for acceptance tests and is useful for debugging purposes when problems occur.

TABLE 5.1.1-1: SEABASS CONFIGURATIONS FOR THE LFASE PROGRAM

<u>Test Name</u>	<u>Marolles #1</u>	<u>Marolles #2</u>	<u>Michigan #1</u>	<u>Michigan #2</u>	<u>Site 534 and Wet Test</u>
Array Configuration	VSP	VSP	VSP	Land Test	At Sea
top of DTU	7-pin Schlumberger	7-pin Schlumberger	7-pin Schlumberger	start with 7-pin change to 14 pin 70m	14-pin WHOI
DTU to Sat #1	30m	70m	30m		10m
Sat #1 - Sat #2	30m	30m	30m	30m	30m
Sat #2 - Sat #3	30m	30m	30m	30m	30m
Sat #3 - Sat #4	30m	30m	30m	30m	30m
Sat #4 - BRG	N/A	N/A	N/A	N/A	10m
DTU configuration	high power	high power	high power	low power	low power
Hydrophone in top satellite ?	no	yes	yes	yes	yes
Casing ID	178mm (7")	178mm (7")	203mm (8")	203mm (8")	276mm (10.88")

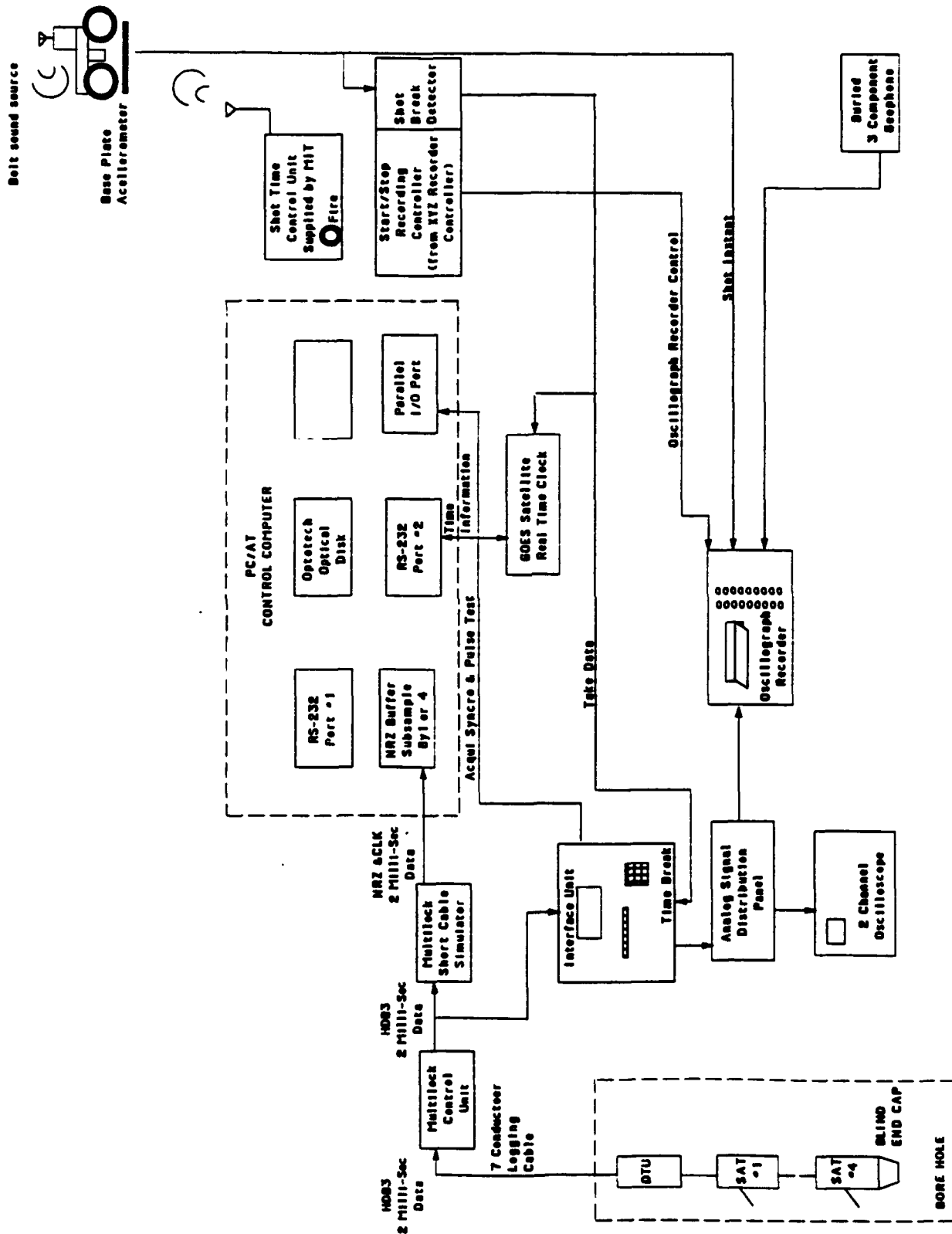


Figure 5.1-1. SEABASS can be used as a VSP tool as in Michigan (see section 6.6). This is also a useful configuration for testing just the Multitlock array components of SEABASS.

5.2 LAND TEST CONFIGURATION

The land test configuration (or short wire test mode) is used for testing the seafloor recording system on land (Table 5.1-1 and Figure 5.2-1). This configuration can also be used to run a land based ambient noise experiment. The four node borehole array is clamped at fixed positions in the borehole at either 10m or 30m separations. The DTU, in low power short cable mode, sits in the recording van on the surface and is connected to the top satellite via 37 conductor cable. The recording van set-up is an exact mock-up of the Bottom Control Unit including batteries and the shipboard recording system.

For controlled source experiments, shot instants and analog recording are controlled in the same fashion as for the VSP mode. Data are acquired on the Optotech optical disk in the 'shipboard' equipment section. However in this case the ACQUISYNCHRO command to the DTU comes from the PC-AT control computer rather than the Interface Unit. The shot controller issues a 'Take Data Command' to the control computer.

Ambient noise records can also be acquired on the optical disks in the DRU based on start time and duration information. For ambient noise tests the power to the 'shipboard' equipment can be shut down (including all generators) and the BCU and DRU acquire data autonomously on battery power.

In Michigan the DTU cable was 70m long and the top satellite was at a depth of 50m. The DTU was connected to the BCU via 14 conductor cable and subsampling was carried out in the BCU. Control functions were carried out from the shipboard PC/AT and they were monitored on the PC/XT. A Bolt land airgun simulated the shooting ship in an at-sea experiment. The subsampled data were 'telemetered' in 'NRZ plus clock' format to the PC/AT. In this configuration the BCU clock could be calibrated to the GOES satellite clock by a time strobe over a separate wire.

In this mode the SEABASS electronics and Multilock are fully integrated but the power supply and data telemetry link (CIEM) used at sea and the Borehole Re-entry Guide (both provided by MPL/SIO) are not in place. This is a useful configuration for debugging the SEABASS system.

5.3 AT SEA CONFIGURATION

The 'at sea' configuration is used for both controlled source and ambient noise experiments on the seafloor (Table 5.1-1 and Figure 5.3-1). While tethered to the BCU, data can be acquired on ship, and after disconnecting the tether, data are acquired autonomously on the seafloor. The system functions as described in Section 3. In this configuration the Borehole Re-entry Guide (provided by MPL/SIO) is attached to the bottom of the borehole array and control functions, power supply, and data telemetry between the ship and BCU are handled over coaxial cable using telemetry interfaces provided by MPL/SIO. For both controlled source and ambient noise acquisition windows start times and durations are specified manually or by

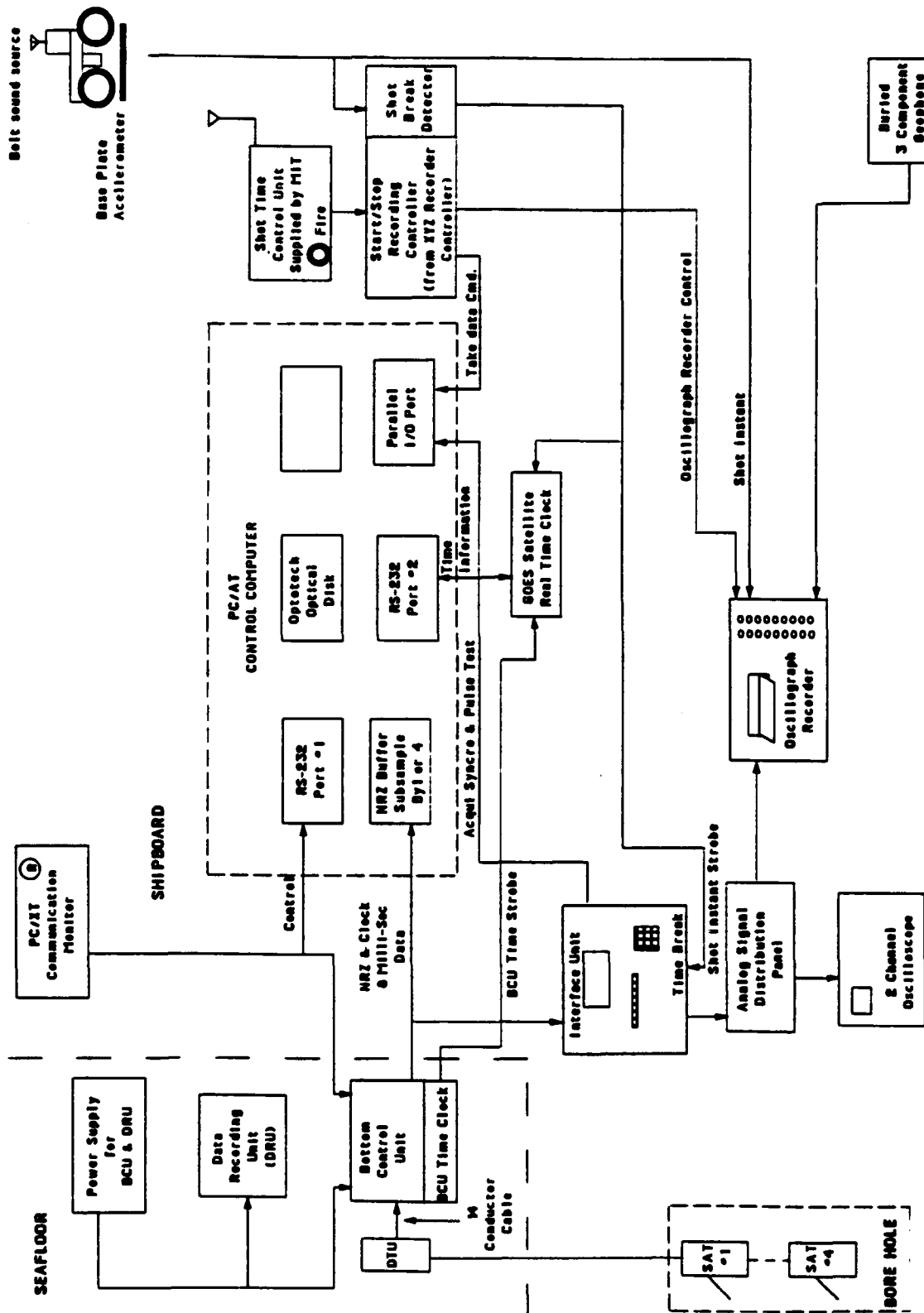


Figure 5.2-1. SEABASS can also be used as an ambient noise acquisition system for boreholes on land. This configuration was used in Michigan to test a mockup of the Multilock array, the Bottom Control Unit and the shipboard electronics. The Borehole Re-entry Guide, thruster and telemetry electronics are not in this configuration.

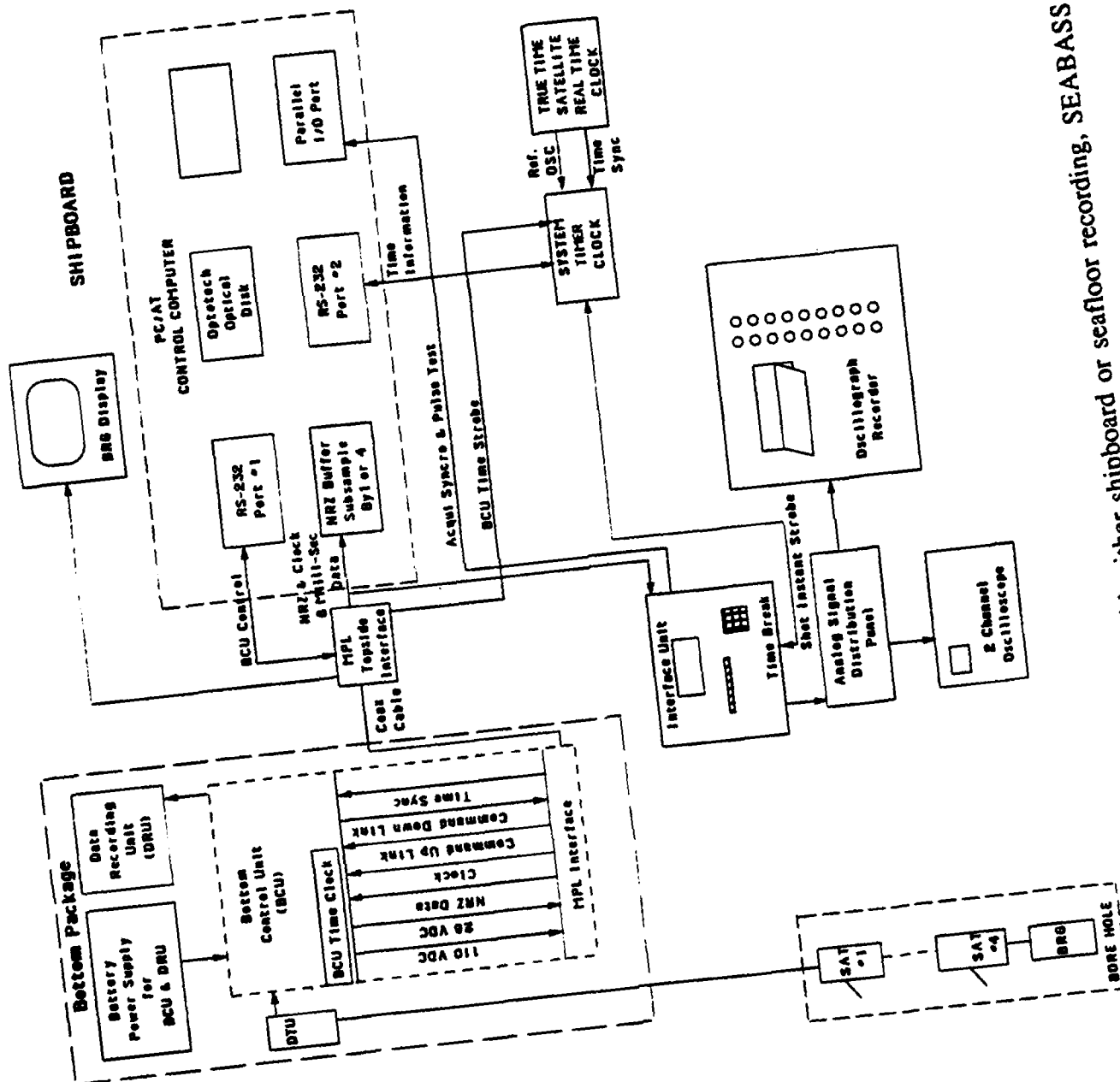


Figure 5.3-1. For a deployment on the seafloor, with either shipboard or seafloor recording, SEABASS is configured as shown.

preprogramming. Shot instants, referenced to the GOES satellite clock, are input in postprocessing.

6. TEST PROCEDURES WITH EXAMPLES

6.1 OVERVIEW

A series of tests were carried out during the SEABASS development program (Table 6.1-1 and Figure 6.1-1). A preliminary sea test of mechanical components of the BIP was carried out from the R/V Melville off the coast of California in the fall of 1988. At the same time the acceptance tests of the Multilock unit were being carried out in France. These consisted of the usual tests to confirm that the array met the mechanical and electrical specifications but also included shake table tests of the satellite clamping mechanism and a borehole test. In January 1989, all of the SEABASS shipboard and seafloor electronics were tested with the Multilock unit in a land borehole in Michigan. In May 1989 the SEABASS system was integrated with the wireline re-entry system (from MPL/SIO) in a wet test on the R/V Melville off Martha's Vineyard. The development culminated in the LFASE experiment off Florida in which borehole data were acquired from the deep sea floor in both shipboard and seafloor recording modes.

6.2 CALIFORNIA TEST CRUISE

A cruise to test the shipboard dynamic positioning system (MPL/SIO) and some of the SEABASS subsystems was carried out off the coast of California in 4500m water depth on the R/V Melville. The port calls were San Diego to San Diego; the site location was 31°40'N 120°10'W; and the cruise dates were October 17-24, 1988.

On this cruise we tested: i) the handling of the Bottom Instrument Package (BIP) frame from the R/V Melville, ii) the cabling, connectors, pressure cases and batteries under actual deep sea conditions, iii) communication with the BCU through the acoustic transponders and iv) the release of the DRU. The BIP frame held the two acoustic transponders, the DRU with its buoyancy and release system (but no recorders), the deep sea batteries and the BCU with a 'bare bones' electronic system.

A problem was detected with the acoustic transponders when WHOI and MPL/SIO gear were run together. (Acoustic signals to the transponders were intended to trigger events in the BCU such as initiating a recording window and releasing the soft tether.) A bug appeared in this system during the California test and the problem was solved on the Martha's Vineyard wet test.

Table 6.1-1: SEABASS Test Schedule

California Wet Test	Off-shore California	October 17-24,1988
Acceptance Tests	Brest, France Massy, France St.Gaudens,France	September 18-30,1988
Shake Table Tests	near Paris, France	August 29,1988 September 26-27,1988
Marolles Borehole Tests	near Paris, France	September 28-30,1988
Michigan Borehole Test	near Travers City, Michigan	January 16-21,1989
Martha's Vineyard Test	off-shore Massachusetts	May 21-23,1989
LFASE	off-shore Florida	August 8-16,1989 September 1-10,1989

6.3 ACCEPTANCE TESTS OF THE MODIFIED MULTILOCK TOOL

The acceptance tests of the Multilock unit were carried out in September 1988 prior to delivery of the array to WHOI. The mechanical tests included tensile tests of the cables, connectors, and sondes (carried out at AMG), and pressure tests of all pressure housings (carried out at IFREMER)(Ateliers Mécaniques de Saint-Gaudens, 1988c). The electrical tests included demonstrations of all the DTU and IU specifications (carried out at Géomécanique) including confirmation of NRE results specific to the WHOI design (Géomécanique, 1988a; 1988b; 1988c). At the same time that the tests were being carried out, training sessions of WHOI personnel on the use and maintenance of both mechanical and electrical aspects of the Multilock array were given.

LFASE Sites

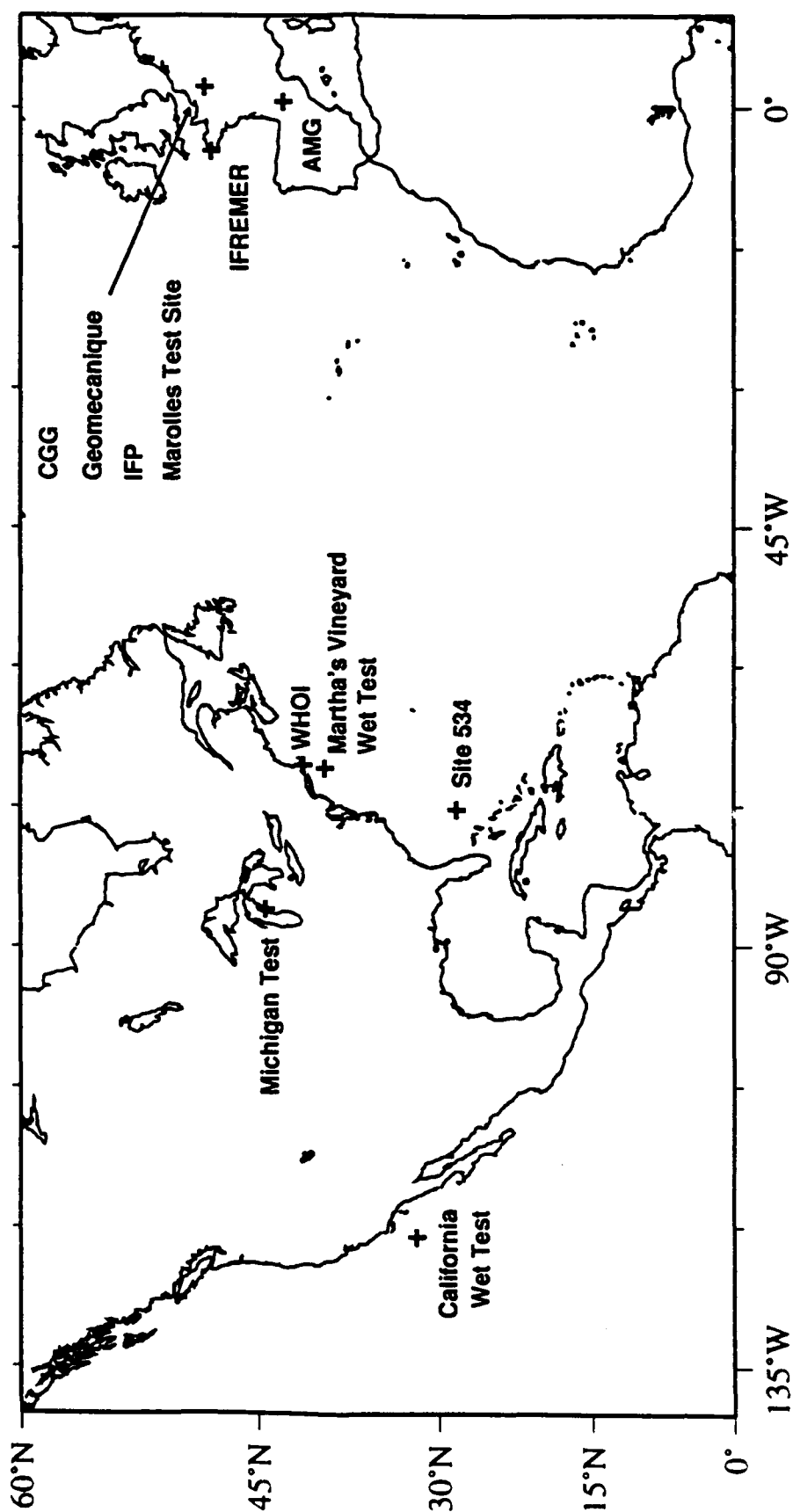


Figure 6.1-1. Testing of the SEABASS equipment was carried out at sites from offshore California to Paris, France.

6.4 SHAKE TABLE TESTS

Resonances of the clamping mechanism can cause ringing and poor quality data in borehole seismic measurements. In order to check for resonances in the sondes used for SEABASS we carried out a series of shake table tests at a vibration test facility near Paris (SOPEMEA, 1988) on 29 August and 26-27 September, 1988. A tank was constructed about 2m high with an inside diameter of 406mm(16.0inch). The whole tank was mounted on a shake table and filled with water (Figure 6.4-1). A Multilock satellite, with or without the optional hydrophone, could be locked in the tank to simulate being clamped in the borehole. Three component accelerometers were placed on the shake table and on the side of the tank in order to check that the tank was moving as a unit and was not itself resonating. The shake table could be vibrated either vertically or horizontally through a range of frequencies from 2.0Hz to 200Hz.

The transfer function between the vertical components of the borehole geophone and the accelerometer on the side of the tank (with the theoretical geophone response applied) is shown in Figure 6.4-2 for the satellite with hydrophone attached. Between 2 and 70Hz the amplitude is within 2dB of unity and the phase is less than 5°. (About 1dB of the amplitude variation could be due to calibration factors between the sensors.) Similar results are obtained for the satellite without a hydrophone except that the fluctuations at 70Hz are not present.

The transfer function between the geophone and the tank for the radial components for a satellite with hydrophone is shown in Figure 6.4-3. The amplitude is within 2dB of unity and the phase is less than 5° from 2Hz to above 40Hz. However at just above 50Hz the amplitude is down 4dB and the phase is almost 40°. Major resonances of 6 to 12dB occur at frequencies above 62Hz however these would be significantly reduced by the anti-aliasing filters in SEABASS. At frequencies above 40Hz the tank does not respond as a unit to the forcing function (the tank response depends on where the reference accelerometer is placed on the tank) so the discrepancies above 40Hz could be artifacts of the test and are not necessarily due to the Multilock clamp.

The transfer function for the transverse components (Figure 6.4-4) is similar to the radial component case with the amplitude within 2dB of unity from 4Hz to 40Hz. Between 2 and 4Hz the amplitude goes down to 3dB below unity and at just above 50Hz the amplitude goes down 5dB below unity. A major resonance of over 20dB is observed at about 180Hz but this is well above the SEABASS passband.

Cross coupling (the signal on the off axis geophones) was generally less than -20dB in the passband. Tests were also carried out for the 9" clamping arm configuration and similar results were obtained.

The results of the vibration tests confirm that the clamping mechanism is ensuring good coupling to 9" and 16" boreholes within 3dB in amplitude and 5° in phase across the passband (2-50Hz) on all three components for satellites with and without the optional hydrophone. The results near 50Hz where the amplitude went down to 5dB below unity



Figure 6.4-1. In order to check for resonances of the clamping configurations used on SEABASS we carried out shake table tests with the sonde clamped in this test cylinder. The response of the tank is monitored by a three component accelerometer mounted on the side and a vertical component geophone mounted on the base of the tank. The forcing function of the vibrator is monitored by a three component accelerometer mounted on the shake table. All seven sensors could be compared with the response of the three component geophones in the sonde inside the tank.

Vibration Test – Vertical Component

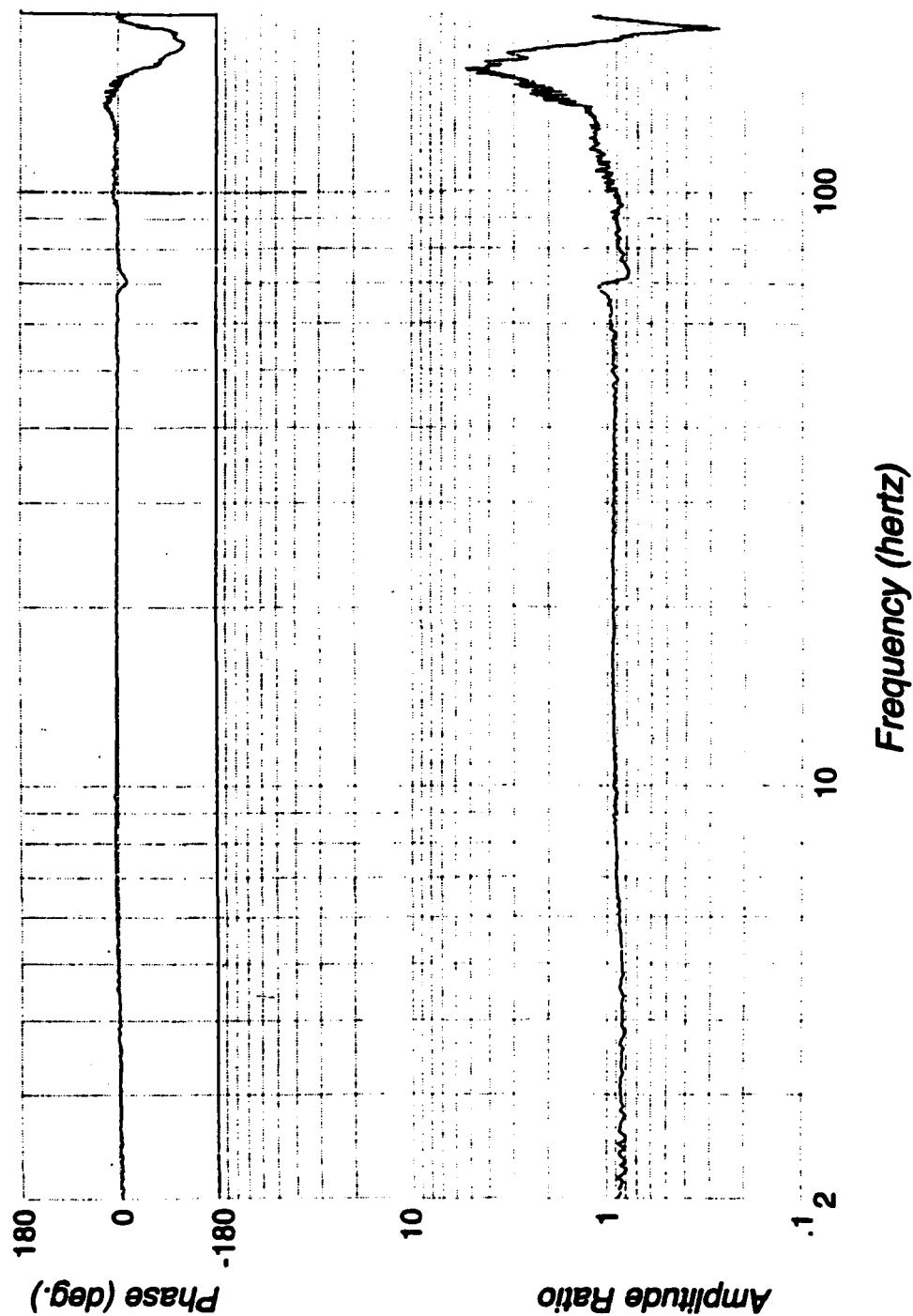


Figure 6.4-2. The transfer function between the vertical accelerometer on the side of the test tank (corrected to velocity) and the vertical geophone in the sonde shows that the sonde is well coupled to the tank in the band from 2.0Hz to over 65Hz. For this test the tank is shaken vertically.

Vibration Test – Radial Component

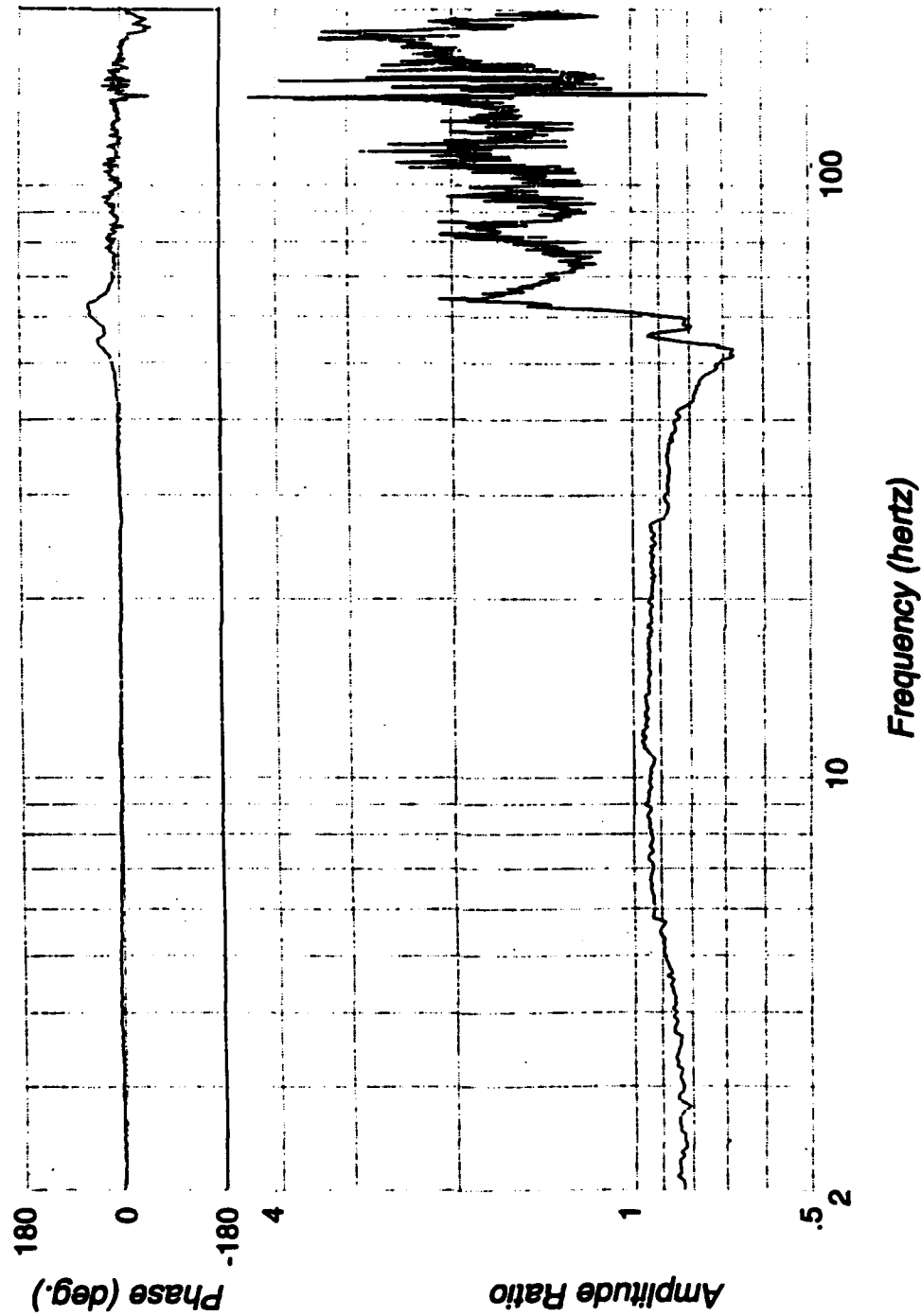


Figure 6.4-3. The transfer function between the radial accelerometer on the side of the test tank (corrected to velocity) and the radial geophone in the sonde is flat with negligible phase shift from below 5.0Hz to over 40Hz. Significant resonances occur above 60Hz, outside the passband of the SEABASS system. For this test the tank is shaken radially. Note that the vertical scale for amplitude differs from Figure 6.4-2.

Vibration Test -- Transverse Component

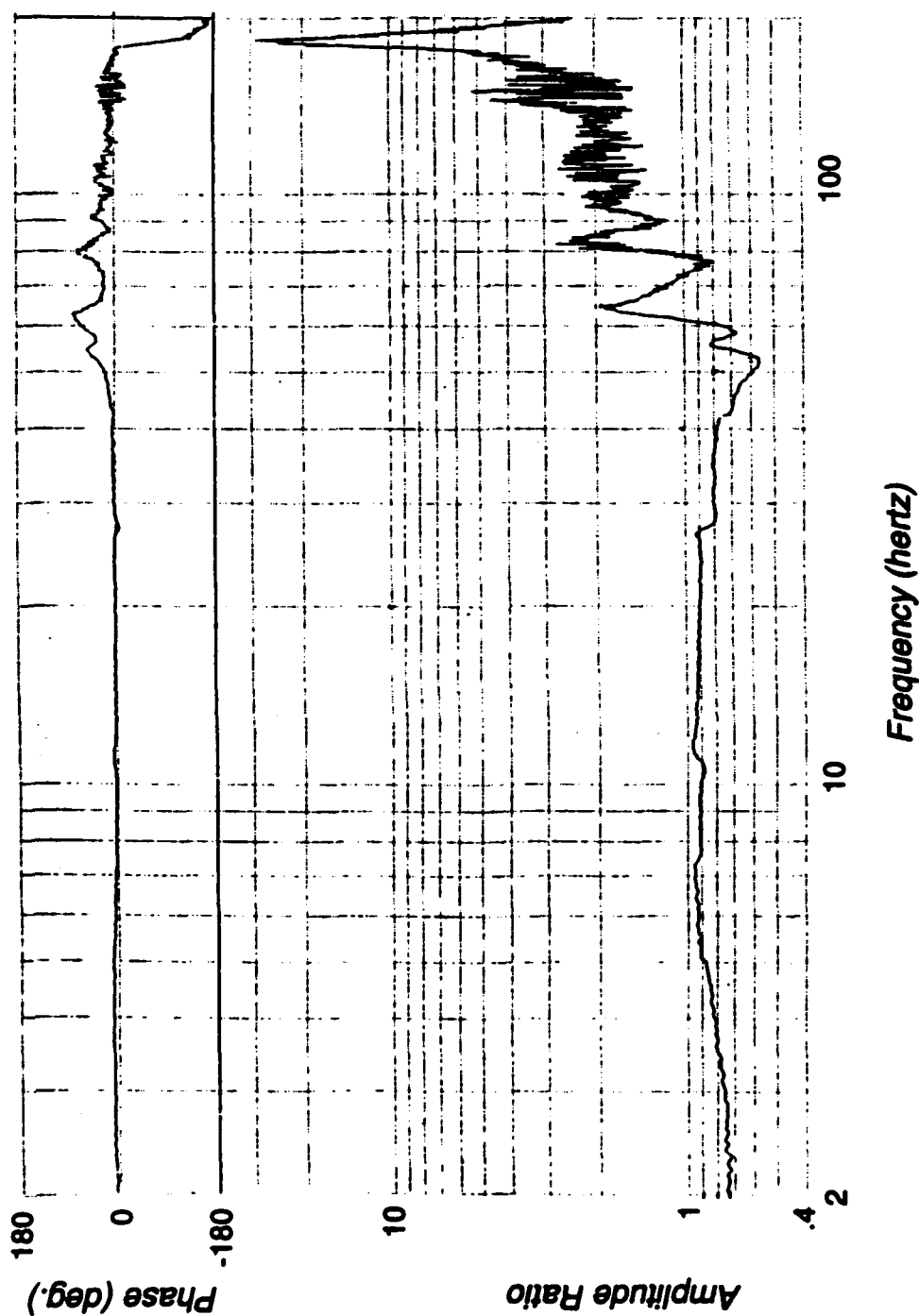


Figure 6.4-4. The transfer function between the transverse accelerometer on the side of the test tank (corrected to velocity) and the transverse geophone in the sonde is flat with negligible phase shift from below 5.0Hz to over 40Hz. A major resonance of over 20dB occurs at about 180Hz, well outside the passband of the SEABASS system. For this test the tank is shaken transversely. Note that the vertical scale for amplitude differs from Figures 6.4-2 and 6.4-3.

probably reflect the inadequacy of the test procedure. Resonances of the system above 50 Hz are sufficiently small that they are adequately damped by the antialiasing filters.

6.5 MAROLLES BOREHOLE TEST

Prior to accepting delivery of the modified Multilock system, an actual borehole deployment of the array in VSP mode was carried out in a test borehole at Marolles, France, near Paris (Compagnie Générale de Géophysique, 1988). The purposes of the field tests were: i) To test the functionality of the modified Multilock array in a field situation. ii) To make WHOI personnel familiar with a field deployment of the Multilock array. iii) To acquire a sample VSP data set in the frequency range 2-40Hz using a Vibroseis source. iv) To collect a sample of ambient noise both deep and shallow in the well between 2-40Hz. None of the shipboard or seafloor recording equipment from SEABASS was available for this test. The program, which was carried out on September 28, 29 and 30, 1988, was very similar to a field demonstration carried out for WHOI personnel at the same site in October 1987.

For this test and the Michigan test the geophones were damped to 0.5 of critical using a 4.32K Ω damping resistor. For the Marolles test, data were acquired at 500 samples/sec rather than the 125 samples/sec used for the rest of the tests.

6.6 MICHIGAN BOREHOLE TEST

A land test of the complete SEABASS system was carried out at the MIT-Burch Site near Travers City, Michigan between January 16 and 21, 1989. The site was selected because it was used often by the MIT VSP Consortium. Logistics were straight forward and a great deal was known about the hole from previous experiments (Turpening, 1990). The objectives of this test were i) to mock up the seafloor configuration of SEABASS in a field situation and to run the system in both "shipboard" and "seafloor" recording modes, ii) to confirm the quality of data from the SEABASS system by running it in VSP mode and comparing the results with other VSP's acquired at the site, iii) to check the effect of casing on the received signals in the band 2-50Hz, iv) to check the effect of tight and slack cables on the acquired signals and noise, and v) to carry out polarization studies of propagation at the site.

Figures 6.6-1 and 6.6-2 show the raw zero offset and 0.6km offset VSP's from the MIT-Burch well. The source is a land airgun. Although further processing is required to enhance reflectors on these sections the data quality is quite good and there are no signs of ringing which would indicate poor coupling to the formation. The noisy trace at about 590m depth is poor quality because the casing is poorly cemented. All VSP systems run at the site show poor results at this depth.

To confirm that all satellites are responding the same we show in Figure 6.6-3 traces from each satellite acquired at the same depth. Since all traces at the same depth are the same by inspection (to within the borehole noise level) we conclude that all sondes are responding

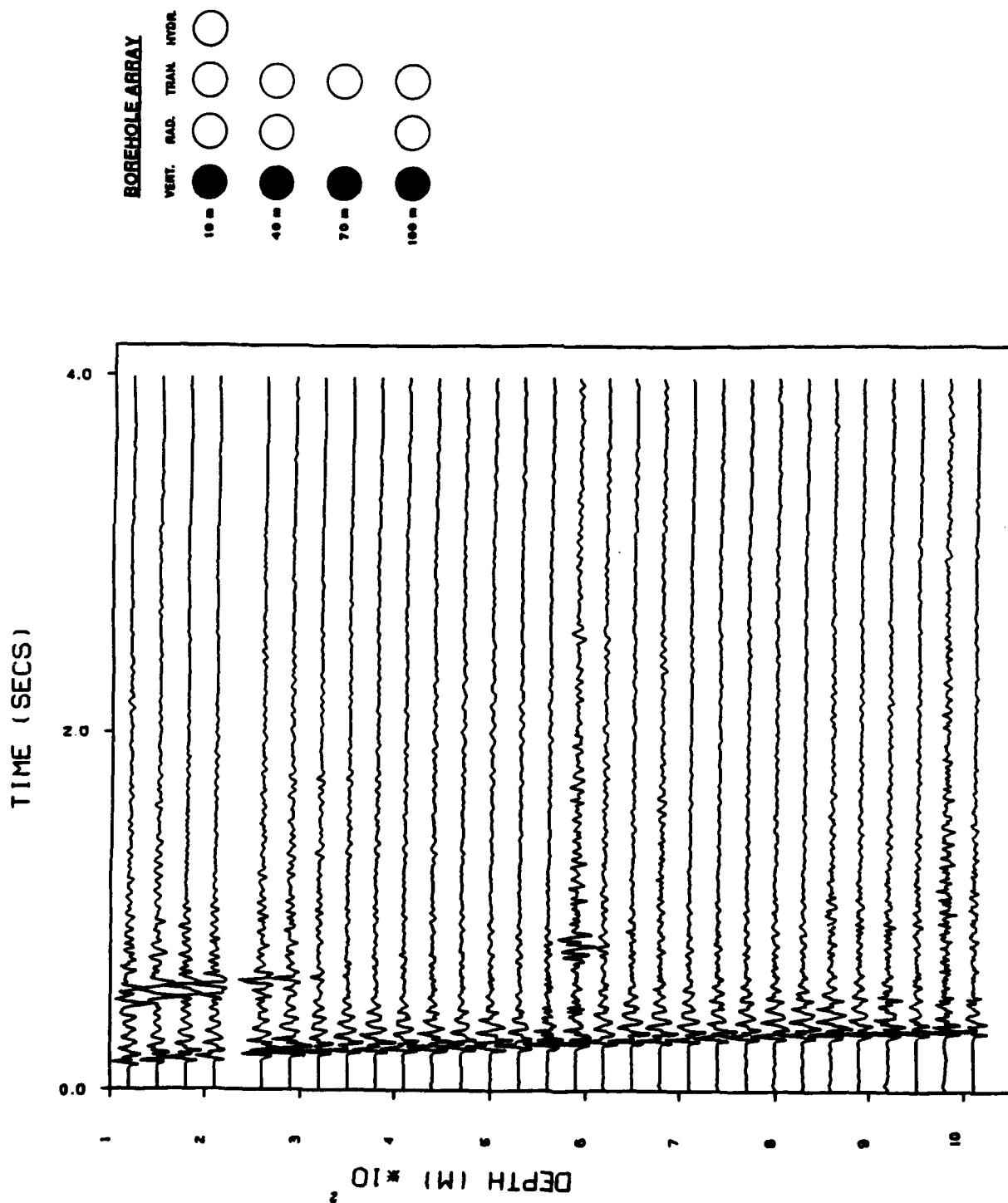


Figure 6.6-1. The zero offset VSP (vertical component) from the Michigan test site shows excellent quality data comparable to other VSP tools run at the site for this bandwidth. The source is a Bolt land airgun.

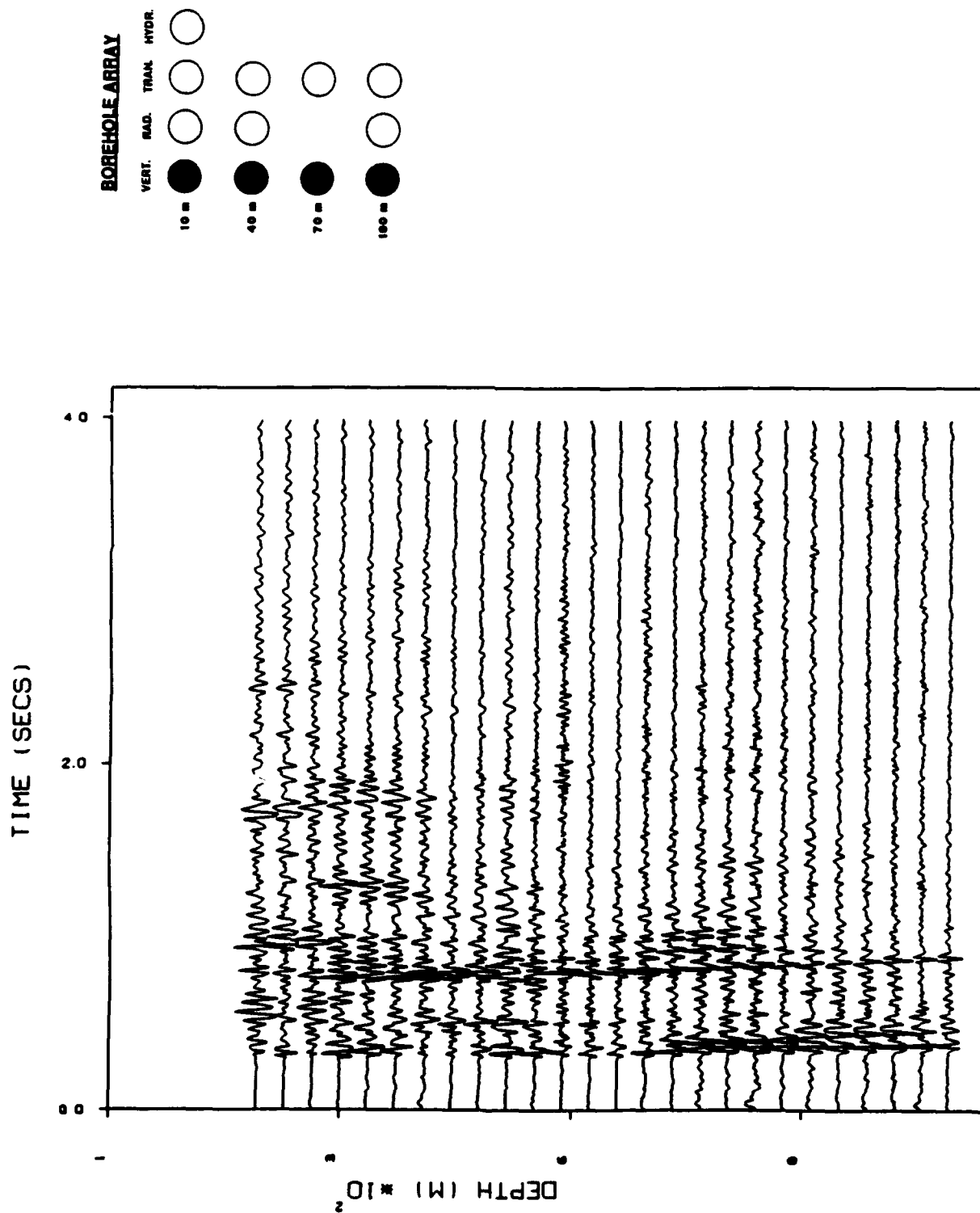


Figure 6.6-2. The offset VSP (0.6km) (vertical component) from the Michigan test site also has excellent quality data.

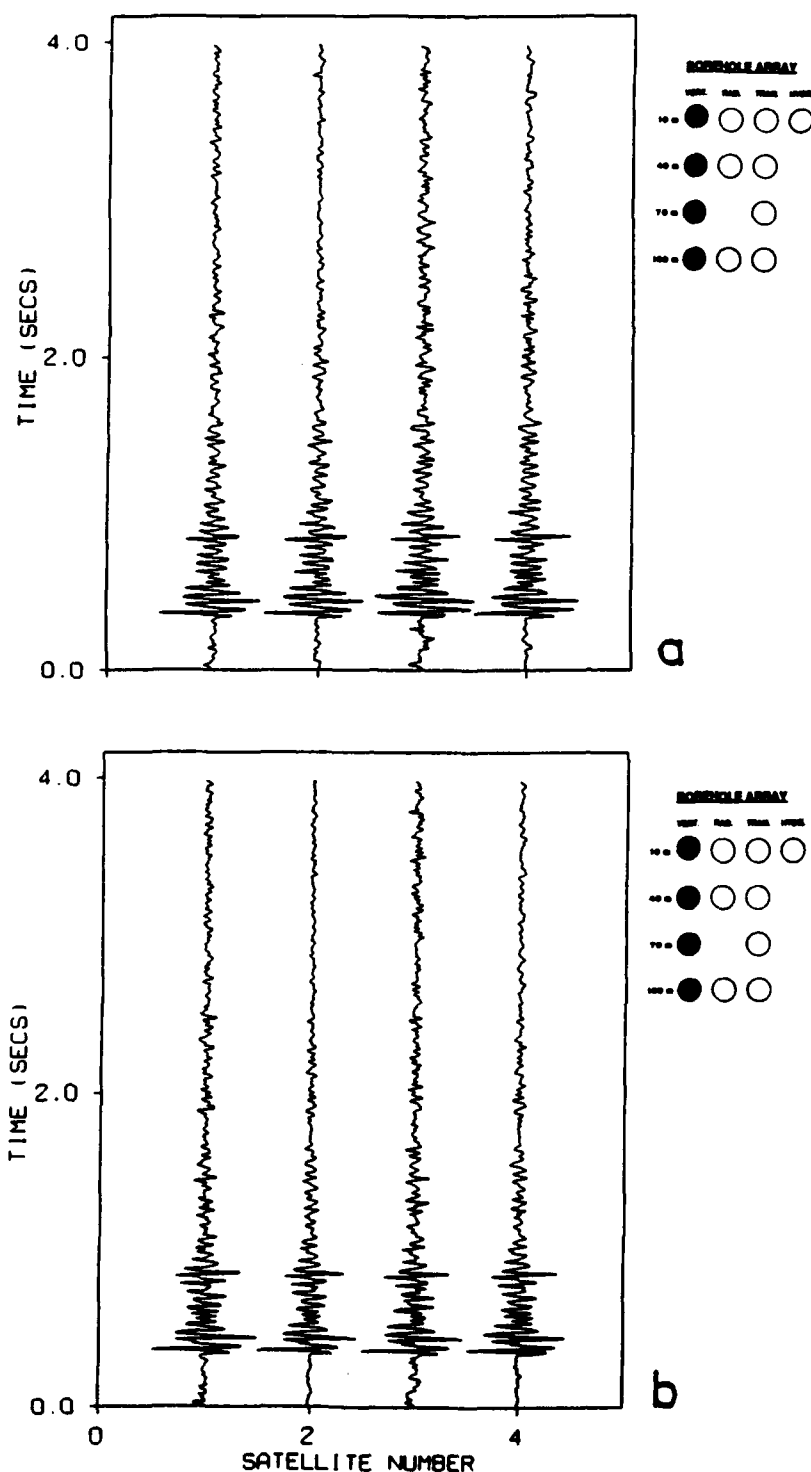


Figure 6.6-3. The response of the four different satellites at the same borehole depth was checked in the Michigan test for a source offset at 0.6km. Figure a) shows the vertical component for all four satellites clamped at the same depth inside casing and Figure b) shows the vertical component of all four satellites clamped at the same depth in open hole below the casing. There are no significant differences in the responses of the satellites.

in the same way. The top sonde has a hydrophone attached and has a slack cable above it; the middle two sondes are identical with taught cables above and below them; and the bottom sonde just has a taught cable above it. We conclude that at these frequencies the effects of taught and slack cable and of adding the hydrophone to the top node are negligible

To check the effect of casing on the seismic signals we compare traces acquired just above and just below the casing shoe at 897m(2944feet) depth (Figure 6.6-4). The traces are essentially identical by inspection, confirming that the casing does not have a significant effect on the seismic signals at these frequencies.

6.7 MARTHA'S VINEYARD WET TEST

The SEABASS system was integrated with the wireline re-entry system in a wet test off Martha's Vineyard in May 1989. The BRG was installed below the Multilock array and the thruster with soft tether was deployed above the BIP. The logistics of deploying the whole array of equipment, which was over 420m long, were developed and tested on this cruise. The whole system was lowered over the side, the clamping arms were released (in open water), clock checks were carried out, the transponders were tested, and data (with the array hanging in the water column) were acquired both internally on the BCU and on board ship. It was confirmed that data from the borehole array could be acquired while the thruster was activated without being contaminated by electrical noise. (During an actual controlled source experiment in ship-board recording mode, it may have been necessary to power the thruster to stay within its watch circle. It was important that borehole data could be acquired with the thruster activated.)

Prior to this test we carried out dock tests on the acoustic transponders and we carried out cold chamber tests at seafloor temperatures of the BCU and DRU. Recorder operation, electrical noise, power consumption and oscillator frequency (in the DTU) were checked. The units functioned to specifications.

6.8 THE FLORIDA DEPLOYMENT (LFASE)

SEABASS was built as one component of the Low Frequency Acoustic Seismic Experiment (LFASE). The principle objective of LFASE was to understand the physics of the excitation and propagation of low frequency signals and ambient noise (2 to 50Hz) immediately above, at and below the seafloor. Since signals and noise can vary considerably over short distances away from an interface it was felt that measurements should be made simultaneously at a number of depths. LFASE was a multi-institutional effort with investigators from the Naval Ocean and Atmospheric Research Laboratory (NOARL), Science Applications International Corporation (SAIC), Scripps Institution of Oceanography (SIO), and Woods Hole Oceanographic Institution (WHOI). The project was co-ordinated by Johns Hopkins University Applied Physics Laboratory.

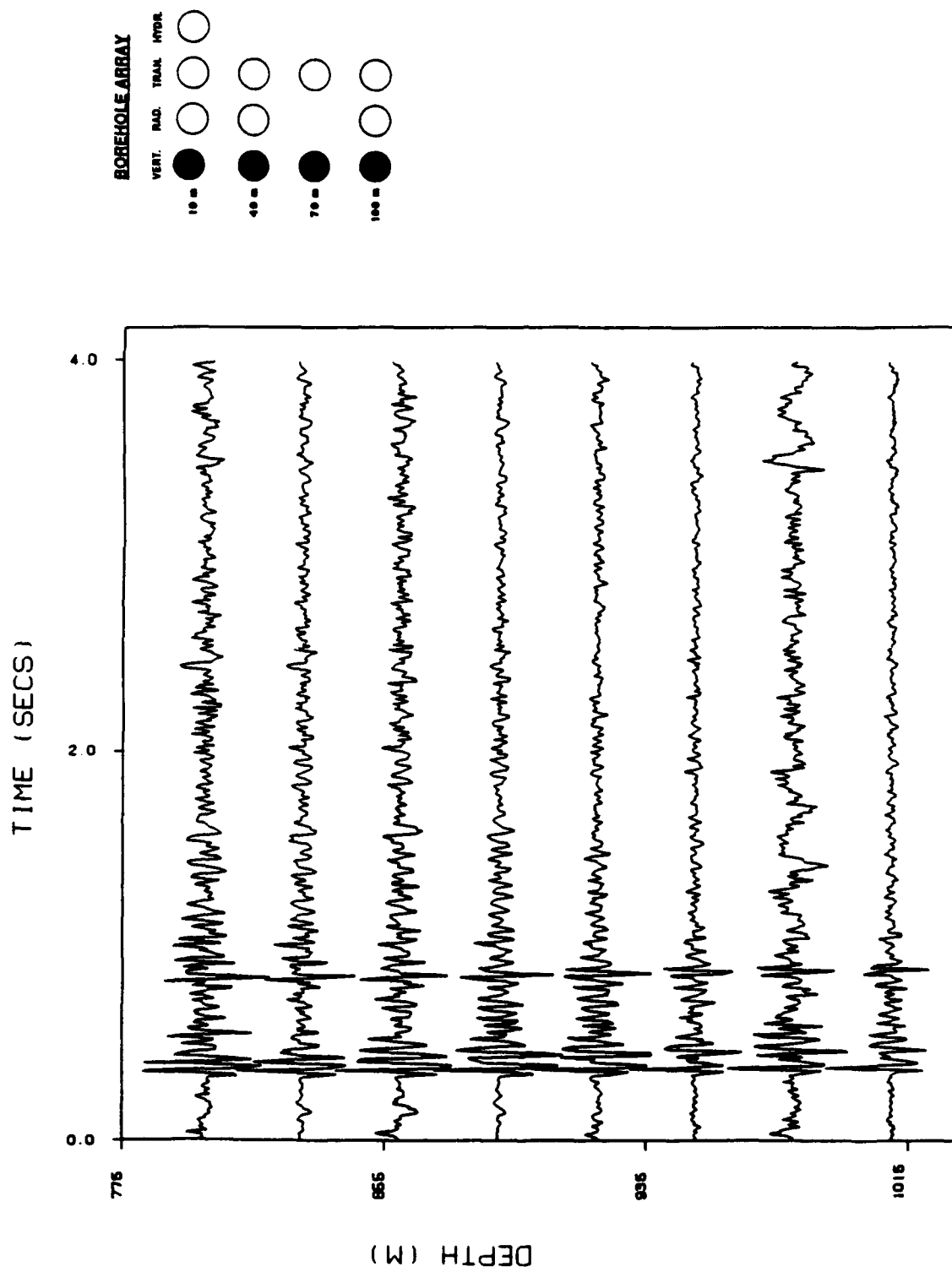


Figure 6.6-4. The effect of casing is shown to be negligible on vertical traces which span the casing shoe at 900m.

SEABASS was deployed on LFASE using the wireline re-entry technique (Spiess *et al*, 1989a; submitted) from the R/V Melville in DSDP Hole 534A, about 250 miles ENE of Miami, Florida (Figure 6.1-1; Sheridan, Gradstein *et al*, 1983). Water depth at the site was 4971m (Table 6.8-1). Ocean Bottom Seismographs (OBS's) and a Vertical Hydrophone Array (VHA) above the seafloor were also deployed. While Melville was on station, and connected to SEABASS via the coaxial tether, a shooting pattern of radial and circular lines was fired using airguns and explosive sources from the USNS Lynch. This phase of the experiment provided data on the propagation characteristics of the area as well as characterizing the geology of the sediments and crust surrounding the site. The soft tether was released and R/V Melville returned to port, leaving SEABASS to acquire ambient noise records over a two week period. SEABASS was recovered by grappling from R/V Melville using the same thruster system that was used on deployment. A summary of the data acquired on SEABASS during LFASE was given by Bolmer *et al* (1991).

SEABASS was configured with sondes at 10, 40, 70, and 100m below the seafloor (BSF). The borehole hydrophone was located in the top sonde with a three component seismometer. In order to remain within the constraint of a twelve channel system, we sacrificed the data from the radial component of the third node (70mBSF). The second and fourth nodes had full three component seismometers (Table 6.8-2). The first, third and fourth nodes were well coupled to the borehole. However the clamping arm on the second node (at 40mBSF) did not release, resulting in poor quality data for this sonde.

Table 6.8-1: Summary of Significant Depths at DSDP Hole 534A

	Depth Below Rig Floor (m)	Depth Below Sea Level (m)	Depth Below Sea Floor (m)
Top of Sediment	4976	4971	
Bottom of 16" Casing	5062	5057	86
Bottom of 11-3/4" Casing	5507	5502	531
Top of Basaltic Basement	6611	6606	1635
Total Depth (9-7/8" open hole)	6642	6637	1666

TABLE: 6.8-2: GEOPHONE CHANNEL ASSIGNMENTS

<u>Channel Number</u>	<u>Component</u>	<u>Depth Below Sea Floor</u>	<u>Satellite Number</u>
1	Vertical	10m	1
2	Transverse	10m	1
3	Radial	10m	1
4	Vertical	40m	2
5	Transverse	40m	2
6	Radial	40m	2
7	Vertical	70m	3
8	Transverse	70m	3
9	Hydrophone	10m	1
10	Vertical	100m	4
11	Transverse	100m	4
12	Radial	100m	4

NOTE: The Multilock geophone cluster is a right hand system. Positive vertical velocity (z) is downward. If positive radial velocity (x) is East, then positive transverse velocity (y) is South. The clamping arm is in line with the radial component and is on the West side, in this convention.

In order to carry out travel time analysis of airgun and explosive record sections it was necessary to record shot instants and first sample times of data streams to better than 0.020sec. This was accomplished on LFASE by referencing all times from the shooting ship (USNS Lynch), the receiving ship (Melville), and all of the remotely recording packages (BIP, OBS's, VHA) to absolute time from a GOES satellite. Although it was not possible in SEABASS to set the BIP clock exactly to satellite time, it was possible to measure the offset between the BIP and satellite clocks (see section 3.4). Times tagged on the SEABASS field records during LFASE were 0.251sec later than satellite time. Raw shot instant times from USNS Lynch were 2.048sec earlier than satellite time. (So the offset between recorded times and shot instant times was 2.299sec.) The offset of the SEABASS clock was checked a number of times during shipboard recording and it was checked after recovery of the BIP package from the seafloor. To a resolution of 1msec the SEABASS clock did not drift at all over the 24 days that it was on the seafloor.

Figure 6.8-1 shows all twelve time series for an 80inch³ airgun at normal incidence. Most of the energy is on the vertical components (channels 1, 4, 7, and 10). The vertical component of the second sonde (channel 4) has a resonance around 17Hz due to the poor coupling. The hydrophone channel (9) has voltage levels about ten times greater than the geophone channels for both signals and noise. This is a consequence of the gain strategy used in the instrumentation (see section 4.3) and does not necessarily mean that the hydrophone is more sensitive. Only channels 4 and 9 saturate the system during airgun shooting. The hydrophone also shows a second arrival, which is not observed on the geophone channels, about one second after the first arrival. This is a reflection of the tube wave in the borehole which was generated when the direct wave hit the seafloor at the top of the well.

Figure 6.8-2 shows all twelve time series for the 80inch³ airgun at approximately 10km offset. Larger relative signals can be seen on the horizontal components corresponding to larger angles of incidence. The resonance of the second sonde persists and the tube wave is still evident on the hydrophone channel.

Figure 6.8-3 shows a record section (time series of ground motion plotted for increasing range) of the vertical component of the top node for an airgun line. The first, large amplitude arrival out to ranges of about 12km is the direct water wave. The largest amplitude arrival at ranges between 12km and 30km is the first water multiple. Beyond 30km the largest amplitude arrival is the second water multiple. A weak head wave from the ocean crust, with a phase velocity of about 6.0km/sec, is observed between 30 and 40km at a time of about 12sec.

Phase velocities across the SEABASS array give a clear indication of the direction of sound incident on the seafloor (Figure 6.8-4). Water waves are incident from above and have later arrival times with depth. Ground waves, turned in velocity gradients well below the seafloor, are incident from below and have earlier arrival times with depth.

Figure 6.8-5 shows polarization diagrams for the bottom node for the direct arrival. The distinct linearity in the polarizations indicates that the sonde is well clamped. The direct wave exhibits linear particle motions which are consistent with theory for body waves. Such

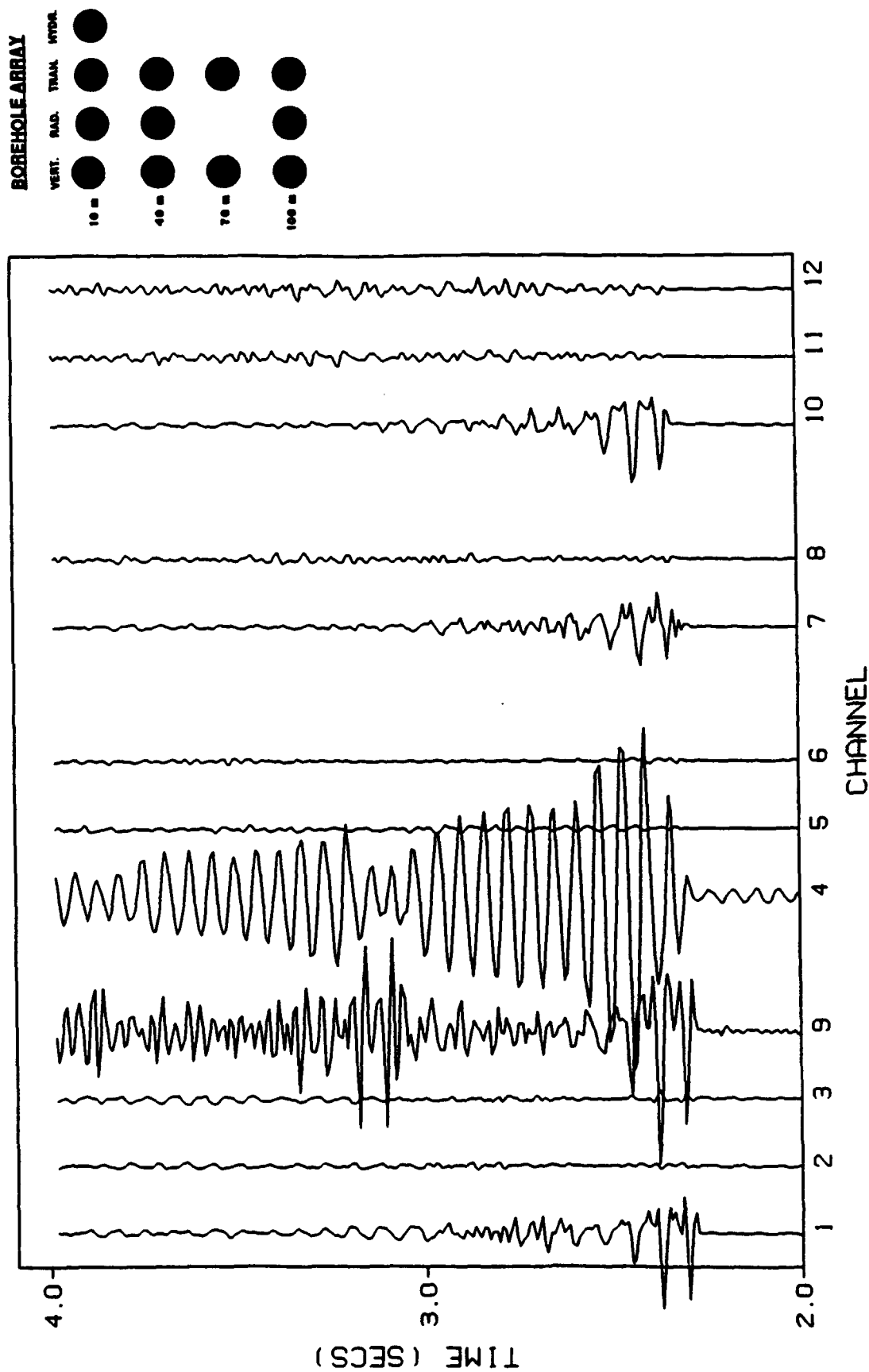


Figure 6.8-1. All twelve SEABASS channels are shown for the seafloor installation on LFASE for an 80inch³ airgun at normal incidence. The strong resonance on channel 4 occurs because this sonde was not clamped. The tube wave can be seen on the hydrophone channel (9) just beyond 3.0sec. Little energy is observed on the horizontal components because the sound is incident directly from above.

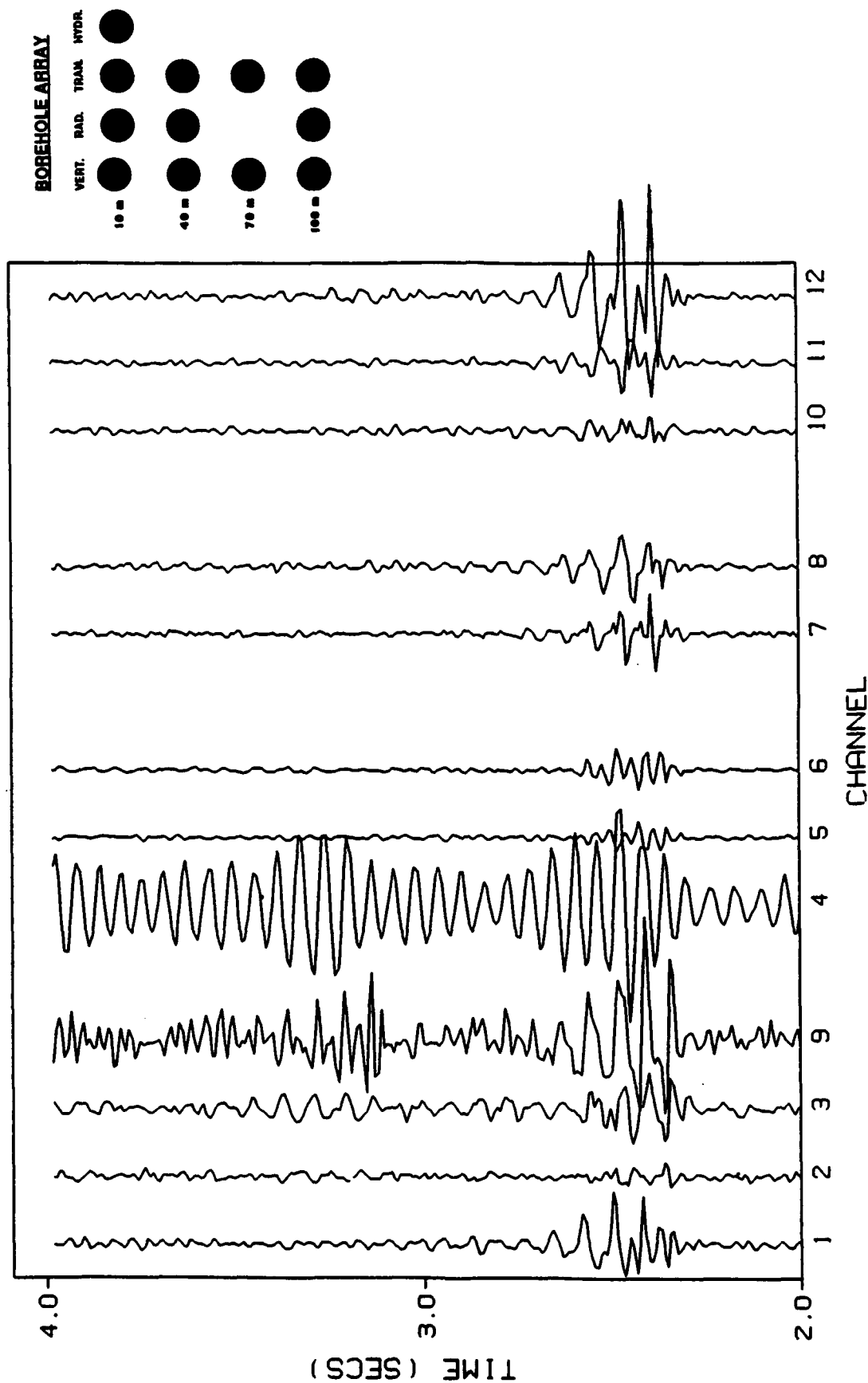


Figure 6.8-2. All twelve SEABASS channels are shown for the seafloor installation on LFASE for an 80inch³ gun at 10 km range. The horizontal components show energy arriving from the side.

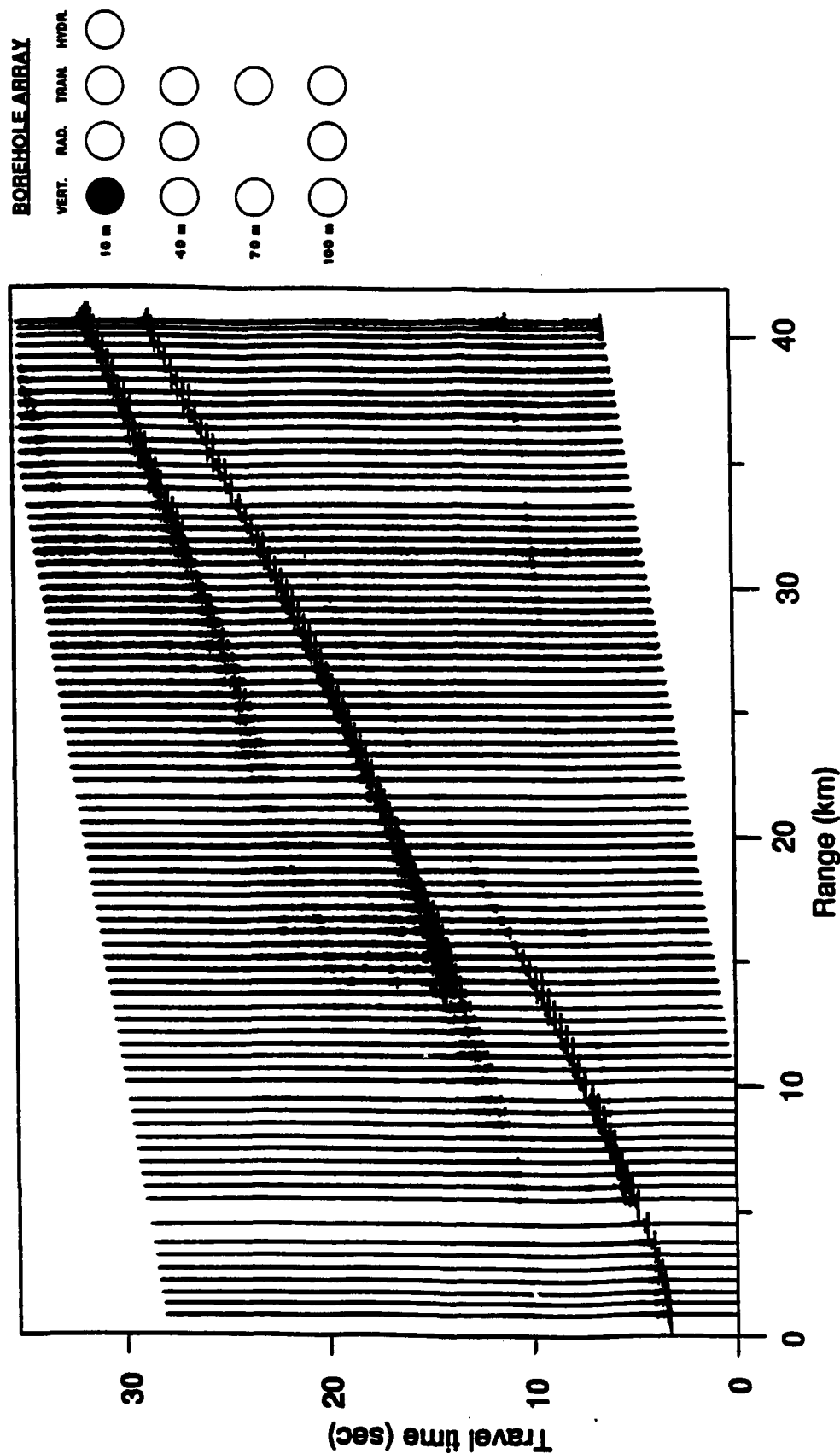


Figure 6.8-3. An airgun refraction line from LFASE shows the distribution of energy with range. The direct (first) path decays beyond 20km. The first water multiple has the dominant energy between about 12 and 25km and the third water multiple is dominant from 25 to 40km. A weak refraction arrival from the subbottom can be seen at ranges from 25 to 40km at about 10 secs. The velocity of this arrival is 6.4k/s indicating that it has penetrated to well within igneous basement.

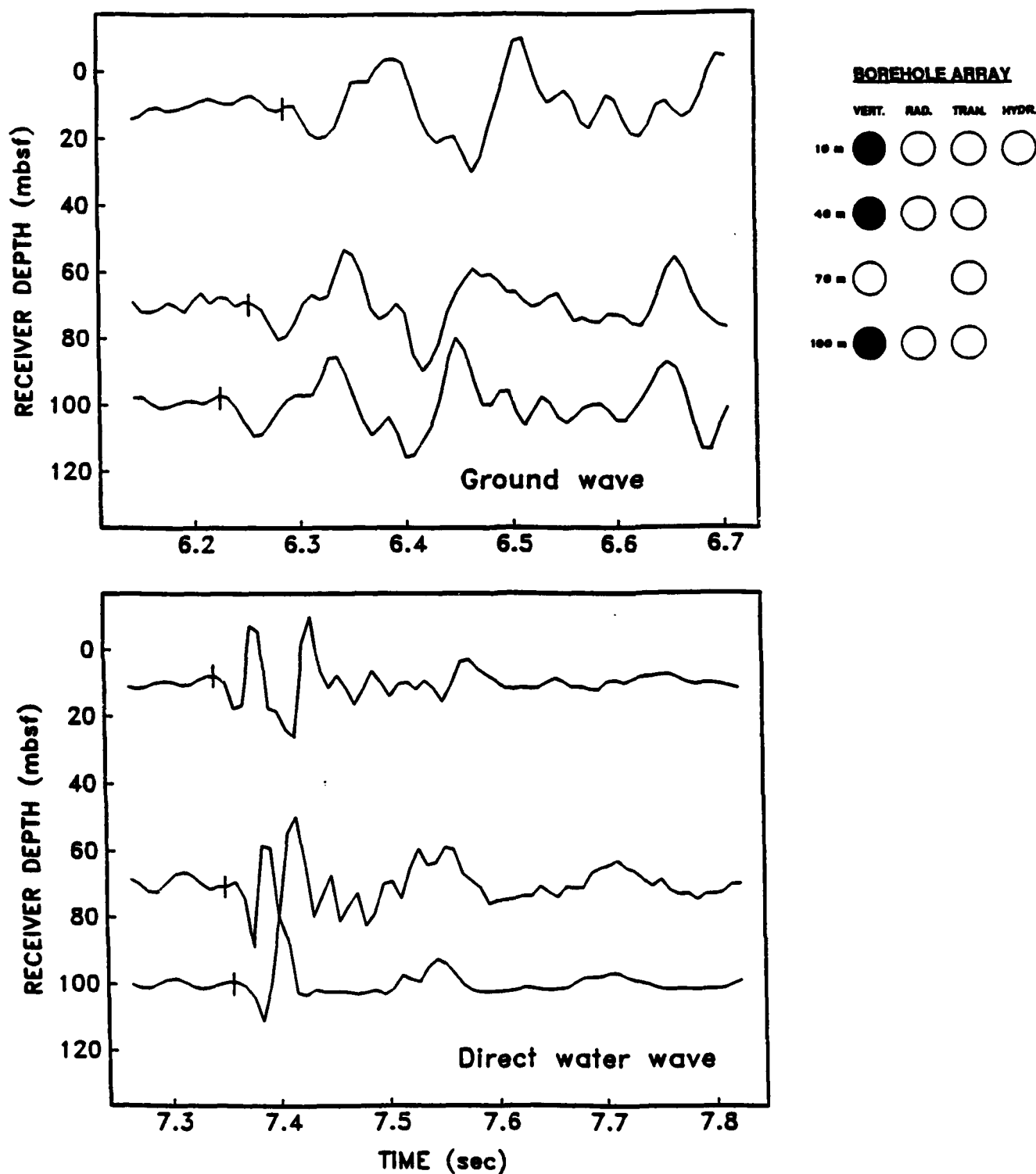


Figure 6.8-4 The arrival times on the various traces across the array indicate that the water wave is coming from above and that the ground wave is coming from below. The shot for this figure is at 10km range.

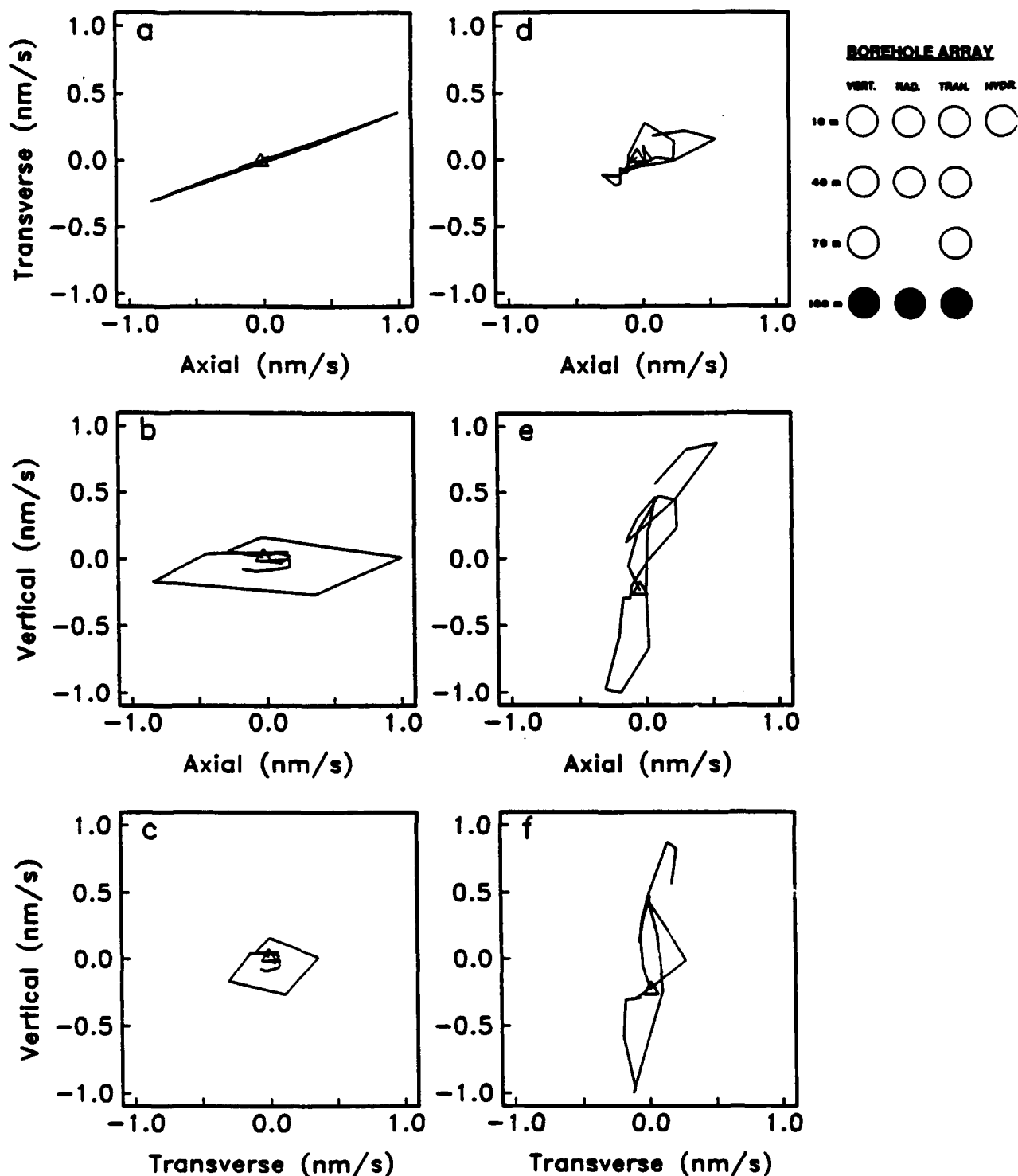


Figure 6.8-5. The polarizations of the water wave (Figures a, b and c) are extremely linear in plan view (a) and point at the source with an azimuthal resolution of less than 5° . The polarizations of the ground wave arrival (Figures d, e and f) are consistent with a compressional wave incident from below. These polarizations correspond to the same shot as Figure 6.8-4.

linear particle motions are rarely observed in field data because seismometers are often poorly coupled to true ground motion and scattering from heterogeneities in the real earth often distorts 'ideal' observations. These plots are the best indicator of the high data quality obtained with SEABASS.

Figure 6.8-6 compares ambient noise levels between the vertical channels at 10m and 100m depth. The ambient noise decreases with depth by up to 12dB between 15 and 50Hz. Since electrical and Brownian noise levels are well below the observed ambient noise (see section 4.2) we are confident that we are measuring true earth noise.

The data acquired by SEABASS on the LFASE experiment are among the best quality seismic data ever obtained from the seafloor. Excellent coupling to the formation ensures faithful response to true ground motion. The coda observed in seafloor measurements, which is caused by a combination of poor coupling and strong interface wave scattering, is virtually eliminated on the borehole data. This is supported by the dramatically linear polarization diagrams (hodograms). System noise is at least 20dB below the observed ambient noise, so that ambient noise studies can be carried out with confidence. Absolute times of seismic events are obtained to ± 5 msec and relative times between data points on different channels are known to within ± 50 µsec.

7. REDUNDANCY, SAFETY FACTORS AND RISK REDUCTION

7.1 OVERVIEW

Because of ship costs and tight scheduling we try to ensure that an experiment will work correctly at sea the first time. A second opportunity to carry out an experiment may take years to occur, if ever. Some systems, like Ocean Bottom Seismometers, can use redundancy to increase the chances of a successful experiment. If ten instruments are deployed and the chances of an instrument failure are fifty percent, there will still be five instruments with good data and at least some of the scientific objectives will be met. However on SEABASS there is only one system and the same fifty per cent chance of failure, which means getting absolutely no scientific data, is unacceptable. In the SEABASS development program we made every effort to anticipate problems that may occur and to design solutions in advance.

7.2 WEAK LINKS

During the development of SEABASS and the wireline re-entry capability there was concern that borehole equipment may get stuck in the DSDP holes and prevent further drilling or other borehole experiments. A weak link system has been built into the array so that the array can be severed in a controlled fashion if a sonde becomes stuck. This leaves a clean end in the hole that can be 'fished' using either wireline or drill pipe 'fishing' tools typically available in the petroleum industry. Our weak link strategy has been approved by the Ocean

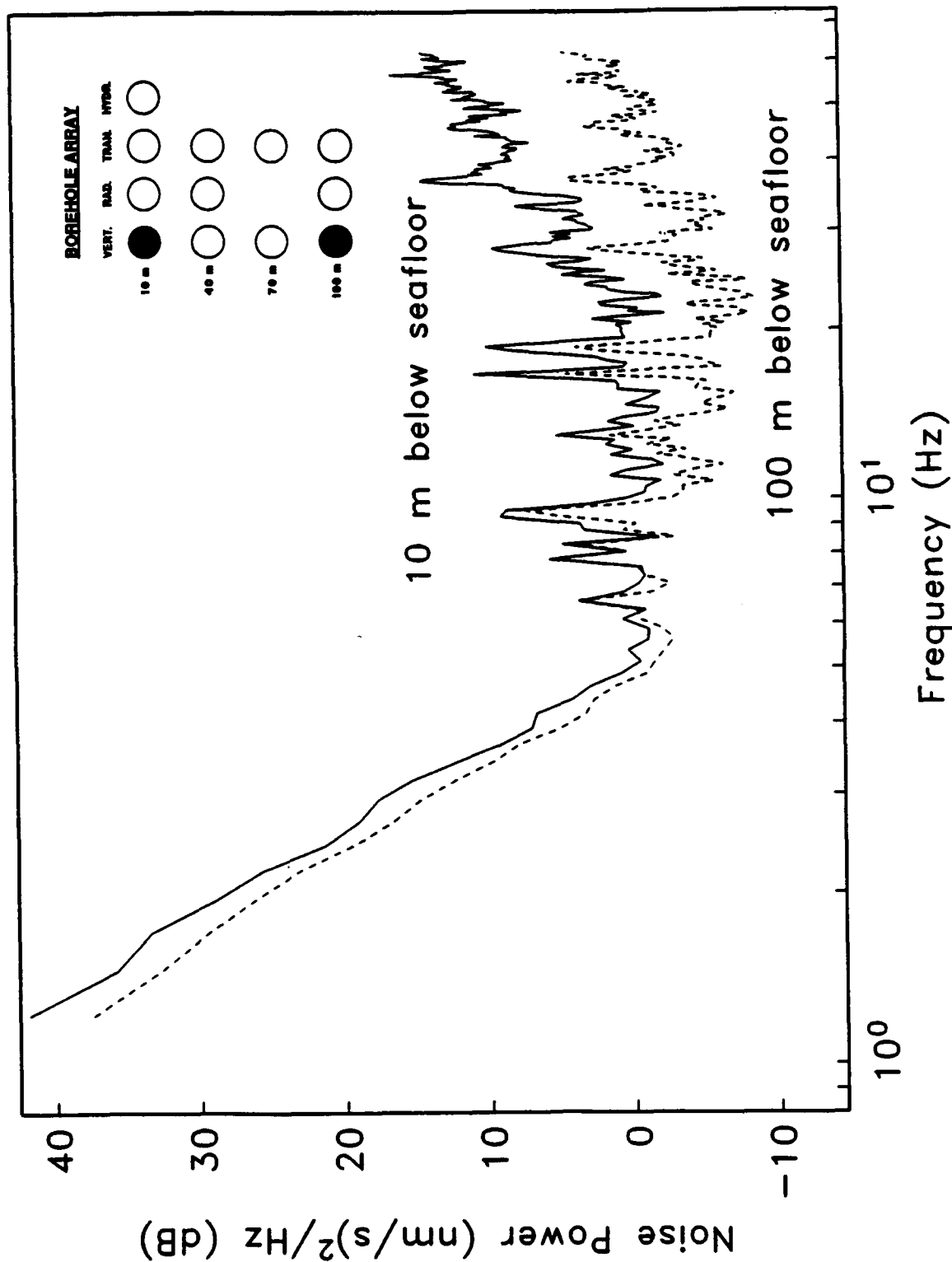


Figure 6.8-6. The ambient noise spectra for the vertical component at 10m and 100m depth shows that noise levels decrease up to 12dB in the upper 100m of the seafloor in the band 15-50Hz. Below 15Hz the spectra are quite similar. (The spectra is based on an interval of 44,997 points (6min) and the averaging window is 512 points.) Note that improved spectra which are more accurate at low frequencies are presented in Bradley and Stephen (in preparation).

Drilling Project (College Station, TX) and they have drawings of the borehole components that may be left in the hole.

In devising a weak-link strategy we assume that the coaxial cable from the ship to the thruster has a yield strength of 9,072daN(20,000lbf). This is the maximum allowable pull at the ship. We further assume that the maximum water depth for operations is 5,500m which gives the maximum immersed weight of the 0.68in coaxial cable as 4,273kg(9,420lbs). Further we estimate that the immersed weight of the thruster is 907kg (2,000lbs) and of the BIP is 427kg(943lbs). This leaves an available pull at the bottom of the BIP of 3,464daN(7,637lbf).

The weak link shearing loads are summarized in Table 7.2-1. The shear pin at the top of the first satellite is designed to shear at a load of 3,175daN(7,000lbf). The nominal breaking strength of the cable between the sondes with both ends fixed is 12,000daN (26,500lbf). Acceptance tests on the cables and connectors have been carried out as follows: i) The cable was tested to rupture by the cable manufacturer to ensure the minimum breaking strength. ii) In order to test the cable connectors, CGG tensile tested a cable assembly to rupture (with the mechanical components of the connectors at each end). No slippage or failure of the cable or connectors occurred at loads less than 6,000daN(13,200lbf). iii) All cable assemblies were proof tested by CGG to 3,200daN(7,040lbf). iv) The satellite and hydrophone housings themselves were proof tested up to 8,000daN(17,600lbf) without damage.

Table 7.2-1 SEABASS Weak Link Shearing Loads

Satellite #1 (top)	7,000 lbs	3,182 daN
Satellite #2	6,000 lbs	2,727 daN
Satellite #3	5,000 lbs	2,272 daN
Satellite #4(bottom)	4,000 lbs	1,818 daN

The tether cable, between the BIP and the thruster, and the tether cable disconnect, at the top of the BIP, (both part of the MPL/SIO deployment system) should have sufficient strength to safely provide a minimum pull of 3,629daN(8,000lbf).

7.3 ACOUSTIC RELEASE OF TETHER AND DRU

It is possible to lose electrical contact to the BIP during shipboard recording mode but to still remain mechanically attached. This occurs if the 0.68" coaxial cable, thruster or soft tether malfunctions. The BIP electronics is designed to go into automatic seafloor record mode if contact is lost to the surface. The capability to release the tether on acoustic command has also been added to the BIP. On LFASE the electrical connection was totally disrupted during tethered mode because of a failure in the thruster and it was necessary to release the BIP by acoustical command.

In the event that the BIP cannot be recovered by grappling after the seafloor recording phase, we have the capability to release the Data Recording Unit separately on acoustic command as discussed in Section 3.2. If necessary it will float to the surface for recovery. This capability was not used on LFASE but it was tested on the California Wet Test and at the WHOI dock.

7.4 ACOUSTICALLY TRIGGERED RECORDING WINDOW

If electrical command is lost with the BIP before the shooting program is completed and shipboard recording is not possible, there are three fall back options. First, there is an automatic recording schedule which acquires six minutes of data every two hours unless the BIP is under control from the ship or is carrying out another function. Second, the look-up table of start times and durations can be loaded with a schedule which only applies if command from the ship is lost. Third, SEABASS has the capability to record a one hour record on acoustic command. The shooting program can be modified to focus key shots in one hour intervals and the BIP can be activated at the required time from either the deployment vessel or the shooting ship. All three of these options can also be used in a single ship program where the same ship deploys SEABASS and carries out the shooting program. On LFASE we used the automatic and look-up table schedules for the shooting program after the tether was released. It was not necessary to invoke the acoustically triggered windows.

7.5 DEFAULT RECORDING PROGRAM

The default recording schedule (on LFASE it was a six minute acquisition every two hours) is programmed directly into the BCU control software and unless overridden by a scheduled interval from the look-up table ensures that data will be acquired whenever the BCU computer is functioning regardless of the state of the EEPROM look-up table, the acoustic transponders, etc.

7.6 SINGLE CABLE DESIGN

From time to time in design meetings it is suggested that separate cables be run in parallel down hole. This seems attractive for SEABASS because the re-entry equipment can then be totally independent of the borehole sensor equipment. For example the Multilock cable could be identical to the standard VSP version. The Borehole Re-entry Guide (BRG), which must be below the Multilock, could have a separate cable to the BIP for transmitting its power and signals.

Experience in other programs suggests however that running two cables in parallel in a borehole greatly increases the risk of failure of the system. A two cable system is more difficult to deploy from the ship. There is a greater chance of chafing or 'hanging-up' on rough edges in the re-entry cone, casing or open borehole. Special care must also be taken to assure

that both cables are torque balanced so that they do not twist around one another and cause a separation.

In order to make SEABASS a one cable system and to improve reliability, four additional conductors were added to the downhole cables and connectors. These conductors simply pass through all the satellites and the DTU and link the BRG with the CIEM in the BCU. The integrity of the connections to the BRG remains the same as the integrity of the connections to the satellites.

7.7 WATCHDOG CIRCUITRY

Occasionally computers can 'hang-up' for unexplained reasons. (On LFASE during a two week period on the seafloor the BCU computer 'hung-up' three times.) In a laboratory environment if the computer 'hangs-up' the operator turns it off and on again. On the seafloor, where autonomous operation for periods up to two months or more is required, this is not possible. The watchdog circuitry is a stand alone logic circuit that checks if the BCU computer is functioning properly and reboots the computer if a problem is encountered. The watchdog circuit resets an interval counter (the watchdog is fed) whenever an acquisition interval is initiated. If an acquisition interval is not initiated (if the watchdog is not 'fed') at least every two hours, the watchdog circuitry reboots the system (the watchdog barks) (see Section 3.3).

7.8 SPARE SONDE AND SPARE PARTS

Since we will be at sea if there is major failure in the system we try to have spares of the main components available at sea for repairs. As part of the SEABASS system we also have one spare satellite and a spare hydrophone so that if a problem occurs in these units we can simply replace them.

7.9 SCAN COUNTER

The scan counter (described in section 3.5) built into the BCU is an excellent feature for detecting data drop-outs in telemetry and recording systems. On LFASE we had data drop-outs due to the telemetry from the seafloor to the ship, due to hiccups in the data buffer used for seafloor recording and also due to read/write errors in the optical disk drives. The scan count helped us to detect the presence and nature of the problems and to minimize the amount of lost data. Without the scan count a problem would be indicated by the file size not being as large as predicted for the acquisition interval and the whole file would be scrapped since it would be impossible to detect where the data gap occurred. With the scan count one can simply pad the missing scans and process the file as usual. Since some files contain an hour of data this can be a major saving.

7.10 OPTICAL DISK SEARCH PATTERNS

A protocol has been written into the software for writing data to the seafloor disks that permits searching all three disks for available space and continuing to write files until space is unavailable on all disks. Even if enough space is not available for a large file on any disk, subsequent smaller files can continue to be written. Also because there are three drives there is some redundancy to minimize the effect of a drive failure. On LFASE a large section of one disk could not be written to, but the system continued to fill the other disks until no available room was left. If this problem had occurred on a system with only one drive the consequences would have been disastrous. The CPU continued to search for available space on the recorders until the battery power was completely drained.

7.11 INDEPENDENT BATTERY ON CLOCK AND TRANSPONDERS

The Webb Clock in the BCU provides the time base for all data acquired on the seafloor. It is important that the clock offset be established on recovery so that the clock drift during the experiment can be established. The clock is powered by a separate battery mounted in the BCU. In the event that all power is drained from the main batteries or if a short circuit occurs elsewhere in the system the clock will continue to maintain accurate time for up to three months after deployment.

Similarly the acoustic transponders must remain alive after all other batteries in the BIP are drained so that, if necessary, the DRU release mechanism can be activated. The transponders can stay in 'sleep' mode for over one year on their own battery supply.

8. DISCUSSION AND SUMMARY

8.1 AMBIENT NOISE ISSUES

A number of previous studies address ambient noise and signal-to-noise issues for island, seafloor, and subseafloor installations in the ULF and VLF bands (.002-50Hz) (for example, Adair *et al* (1986), Duennebie *et al* (1987), Hedlin and Orcutt (1989), Sutton and Barstow (1990)). The goal of these studies is to determine the optimum sensor strategy for particular applications. Hedlin and Orcutt (1989), for example conclude that a borehole sensor (in their case the MSS) has 'significantly lower noise levels than seismometers on the ocean bottom or on islands' for frequencies above 0.2Hz. The implication of their work is that the worldwide seismic net can be extended to the seafloor (to obtain better worldwide coverage for inversions for earth structure) without compromising data quality and signal-to-noise ratios. The LFASE experiment specifically addresses the issue of how ambient noise varies with depth below the seafloor in a sedimentary environment. SEABASS provides the capability to simultaneously acquire ambient noise and controlled source data at a number of depths in a borehole on the seafloor without a ship present which may contaminate the results.

Figure 8.1-1 compares a sample of ambient noise from LFASE with results from the MSS (Adair *et al*, 1986) and the OSS (Duennebie *et al*, 1987). The LFASE data are from 100m depth in sediments in the Blake-Bahama Basin. (These are similar but not the same data that are shown in Figure 6.8-6 to demonstrate that noise levels decrease with depth below the seafloor on the LFASE array.) The MSS data are from a depth of 54m within basaltic basement, in an area with 70m of sediment cover, near the Tonga Trench. The OSS data are from a depth of 22m in basement, in an area with 356m of sediment cover, off Hokaido, Japan. All sites are in water depths greater than 5,000m. Both the MSS and OSS data are from open, uncased holes and the LFASE data are from a cased hole. Below 4.0Hz, on the upper edge of the microseism band, the OSS and LFASE curves are similar and both are about 6dB higher than the MSS data. These levels should correlate with ocean swell above each site. At the low end of the shipping noise band, between 6.0 and 20Hz, LFASE is about 6dB noisier than MSS and about 12dB noisier than OSS. LFASE is expected to be noisier in this band because of its proximity to the sealanes along the U.S. East Coast. MSS is the furthest of the three sites from shipping traffic, and it is not clear why it is noisier than OSS in the shipping band. MSS data are not available above 20Hz, but in this band LFASE is about 6dB noisier than OSS, consistent with its proximity to shipping lanes. In general, all three sites appear to have the same ambient noise characteristics with discrepancies of less than 20dB.

As discussed in Section 4.1 there is not a simple correspondence between the pressure level observed in boreholes (either on land or in the seafloor) and the ground motion measured by clamping to the borehole wall. This is particularly true for the tube waves generated by controlled sources. The signal-to-noise ratio for the tube wave is at least 40dB greater for a borehole hydrophone than a colocated geophone. However even ambient noise levels do not correlate. The ratio of vertical velocity to borehole pressure for ambient noise varies by almost 40dB depending on environment (geographic location, depth in the well, etc). The physical mechanisms responsible for the ambient noise in the pressure field in boreholes

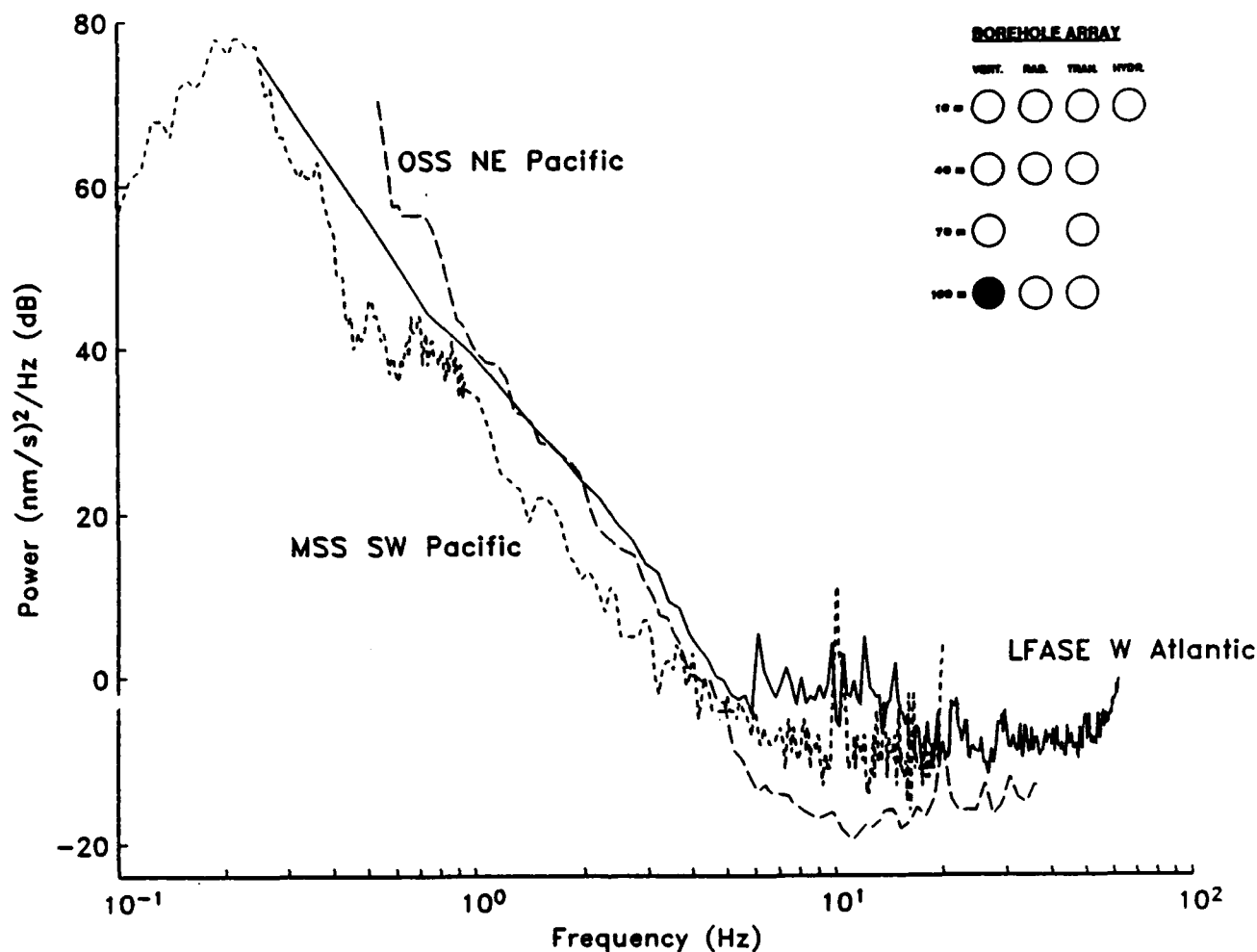


Figure 8.1-1. The ambient noise from LFASE, at 100m depth in sediments in the Blake-Bahama Basin, is comparable to other subseafloor observations acquired by the MSS (at 124mBSF and 54m within basaltic basement, near the Tonga Trench) and the OSS (at 378mBSF and 22m into basement off Hokaido, Japan). Below 4.0Hz, in the microseism band, the OSS and LFASE curves are similar and both are about 6dB higher than the MSS data. In the shipping noise band, between 6.0 and 20Hz, LFASE is about 6dB noisier than MSS and about 12dB noisier than OSS. MSS data are not available above 20Hz, but in this band LFASE is about 6dB noisier than OSS. (For the LFASE spectra the window length is 44,997 points (6min) and the averaging window is 512 points. The OSS curve is from Duennebie *et al* (1987) and the MSS curve is from Adair *et al* (1986). The results are presented as ground velocity at the geophone.)

are different than for ambient noise in the colocated velocity field. A lack of correspondence between pressure and ground motion for ocean bottom installations has been noted by Adair *et al* (1988). However we expect that the physics governing the relationship between pressure and ground motion would be different for ocean bottom and borehole installations.

This paper has presented examples of ambient borehole pressure and three component ground velocity as acquired by SEABASS in two land boreholes and one seafloor borehole. Comparisons have been made with observations at the quietest land stations and at previous seafloor borehole installations. Many factors (such as wind, sea state, shipping, depth of sensor, rock type at sensor, presence of casing, fluid flow in the borehole, cultural noise, etc) can affect the ambient noise in these environments in various frequency bands. Given these factors it is remarkable how similar the ambient noise fields are. These rough quicklook comparisons based on a half dozen sites suggest that throughout the world 'baseline' ambient noise in the frequency band 2-50Hz differs by less than 20dB. ('Baseline' ambient noise means that we take the quietest spectrum in each data set before doing the comparisons.) There is almost as much variability in spectra between sensors at 10 and 100m depth in the seafloor as there is between sensors in the seafloor and the Paris basin (compare Figure 4.2-6 with Figure 6.8-6). A more thorough study of the source and propagation mechanisms of ambient noise in boreholes, considering the wide variety of contributing factors, is warranted and is beyond the scope of this paper.

8.2 TECHNICAL ISSUES

The SEABASS equipment is available for future experiments to study the ambient noise in the seafloor, the physics of sound propagation at and below the seafloor, and the geological structure of the sediments and crust in the deep sea. Future deployments of SEABASS in boreholes on the seafloor can use either wireline re-entry from a surface ship (Spiess *et al*, 1989a; submitted) or submersible assisted re-entry (Legrand *et al*, 1989). However the array cannot be deployed through the drill pipe from the JOIDES Resolution since the outside diameter of the sondes exceeds the inside diameter of the pipe.

Although SEABASS has been designed for a VLF passband of 2-50Hz it obtains useful ULF ambient noise data down to 0.3Hz (Bradley and Stephen, 1992). The polarization and depth dependence of the sound field down to these frequencies can be directly measured. As currently configured SEABASS can be used for ULF as well as VLF studies.

SEABASS can be modified for use with different borehole sensors such as a broadband seismometer (1,000sec-10Hz) for earthquake studies or a high frequency array (10-250Hz) for conventional VSP's. SEABASS can also be used in land boreholes to carry out conventional VSP's or to acquire ambient noise levels at a number of depths simultaneously.

It is not necessary to have a borehole to use the seafloor control and recording package. The SEABASS BCU can be used with ocean bottom seismometers or shallowly

buried seismometers. In this configuration it has advantages over conventional OBS's. Control over the seafloor package via the coaxial tether and cable to the ship gives considerable engineering flexibility to the bottom package. Equipment for implanting a shallow buried instrument (either 'washing-in' for sediments or using a remotely operated drilling device for hard rocks) can receive power and command signals over the coaxial cable. Television can be used to monitor the emplacement process. After installation the seismometer response can be checked on board ship and postemplacement procedures (such as levelling the seismometers and coupling tests) can be carried out prior to leaving the installation in autonomous mode.

SEABASS is a robust and calibrated system for acquiring, reducing and analysing seismic data in the band 2-50Hz below the seafloor. System noise is sufficiently low that authentic ambient noise can be acquired in all but the quietest earth environments. The seismic sensors are well coupled to the formation in both cased and uncased holes. The Multilock clamping mechanism used on SEABASS has no resonances in the observation band. Considerable effort has been expended to anticipate potential problems and to build redundancy and safety procedures which will optimize the chances of recovering excellent quality data. As part of the acquisition system, SEABASS has a quicklook quality control capability. There is also extensive postprocessing software for analysing and displaying the scientific results and distributing and archiving the data.

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